Characterization of goniochromism: current status and pending challenges

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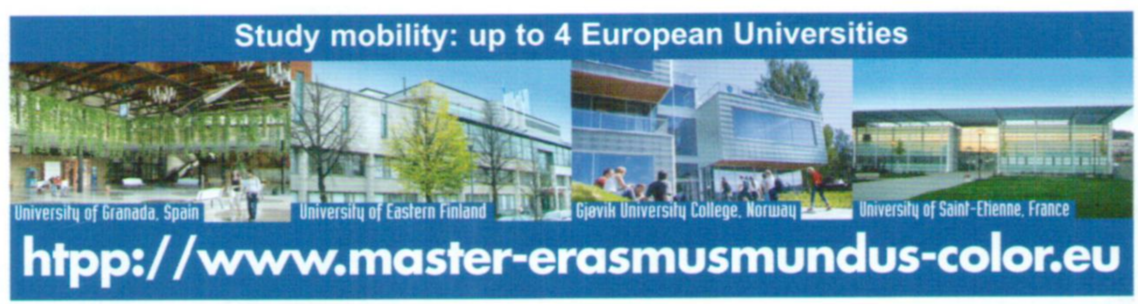
COLOR IN INFORMATICS AND MEDIA TECHNOLOGY



Outline

- What is? How is it measured and perceived?
  - Current instrumentation and standards
- How these visual effects are caused by?
- New findings from the GVC-UA
- Future challenges:
  - Modeling and prediction of visual appearance
  - New materials and process technologies
  - Visual appearance matching control management

What is goniochromism?

- **Abrupt color change due to the light source and observer angle variations**
  - **Lightness and chroma variations**
  - **Texture variations: sparkle (glitter), graininess, etc**

Economical impact of goniochromism

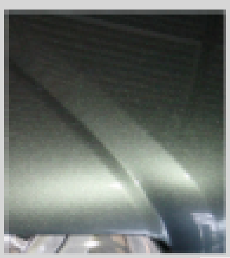
- Industrial applications
  - Special-effect pigments
    - Metallic, pearlescent (iridescent) pigments
  - Automotive coatings
  - Plastics
  - Cosmetics
  - Security inks
  - Building materials
  - Computer graphics
    - Virtual Reality, etc

Economical impact of goniochromism

- **80 % of automotive coatings are effect coatings**

- Metallic coatings accentuate the curved profile: Light – Dark Flop

- Pearlescent coatings result in a more spectacular color effect: Color Flop



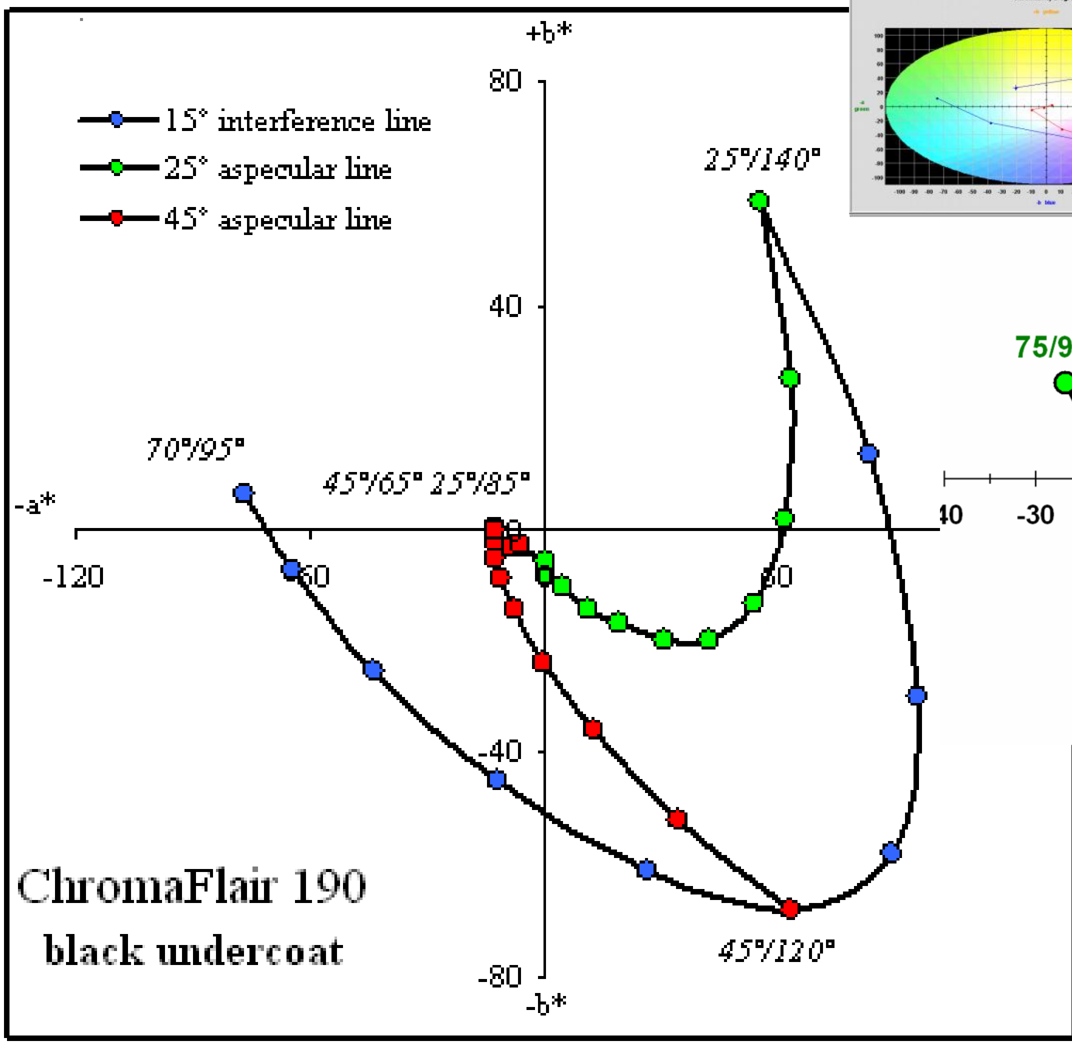
- Effect finishes with special glitter effect (Xirallics™)

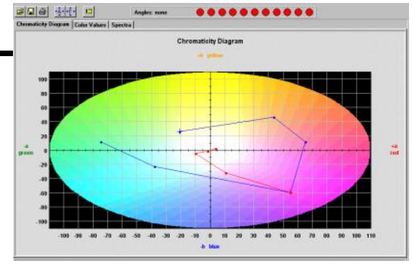
Photo: Courtesy of MERCK

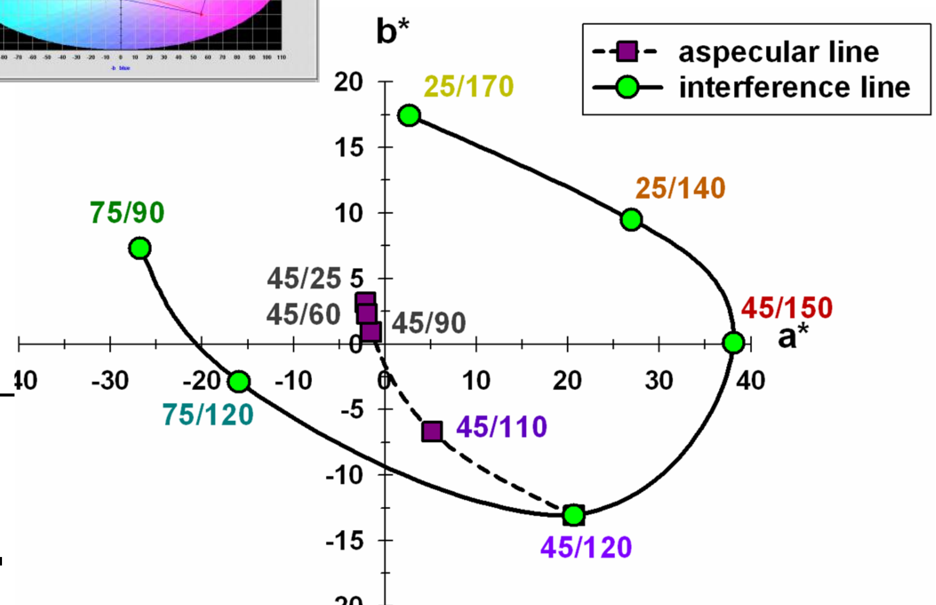
Practical demonstration with GVB

- **Gonio-Vision-Box as portable lighting booth**
  - **Sample: Viola Fantasy – Merck**
  - **http://blog.goniovision.com/gonio-vision-box/portable-gvb/**

How are these color changes?



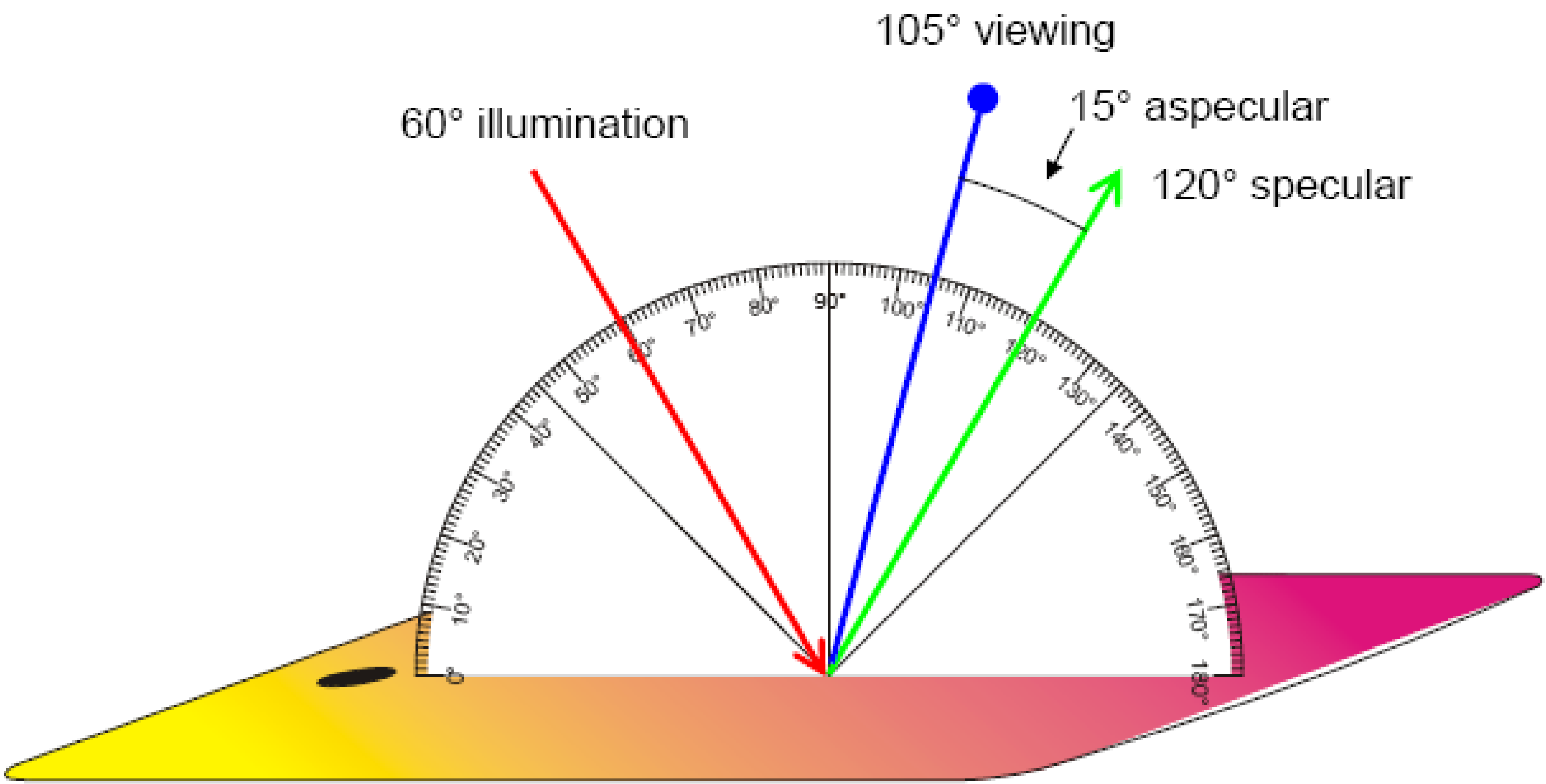




Colorstream T20-02
Arctic Fire Exterior
(T20-02) PSD 5-40 mm Rutile

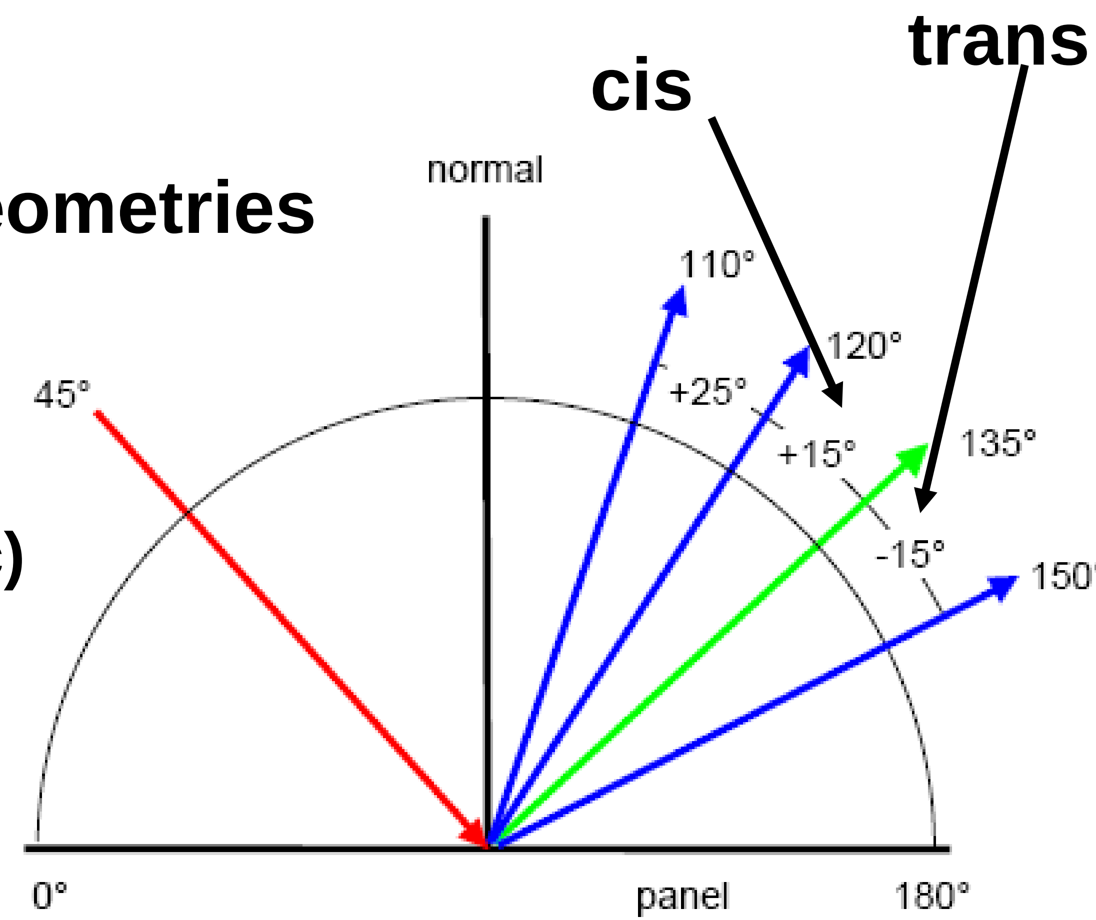
Measurement geometries

- 1st approximation to recommended notation:



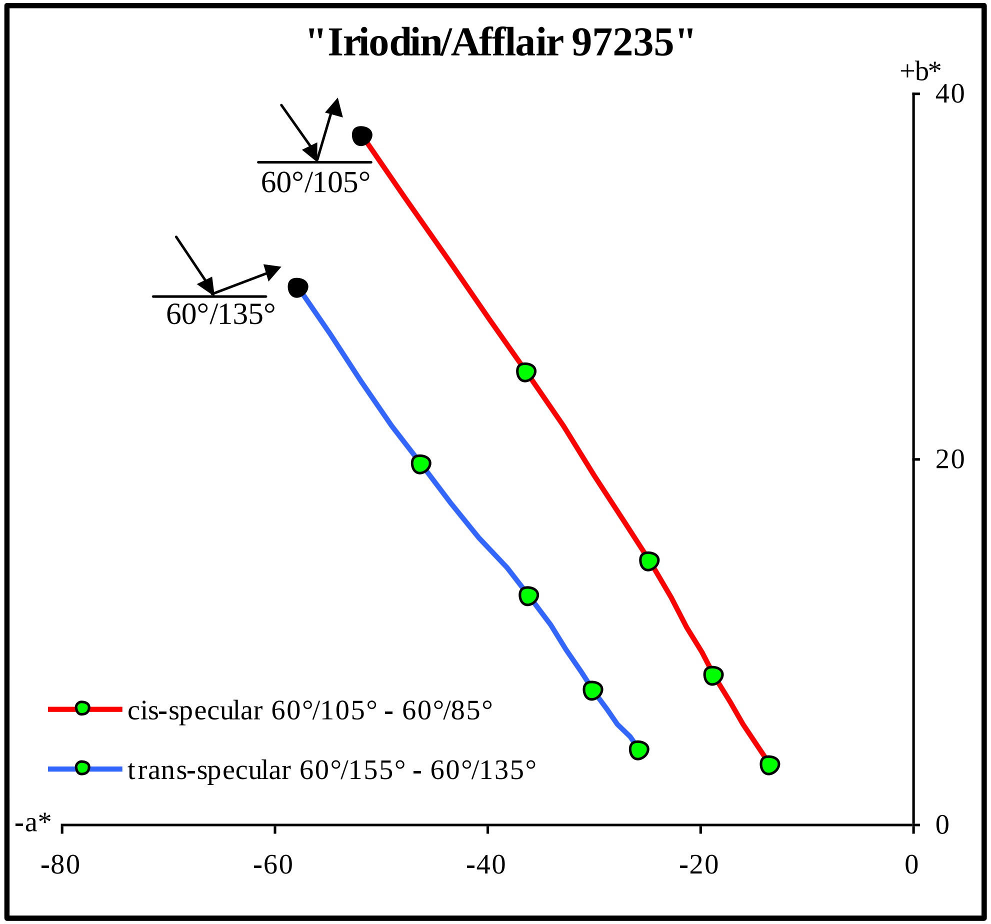
Measurement geometries

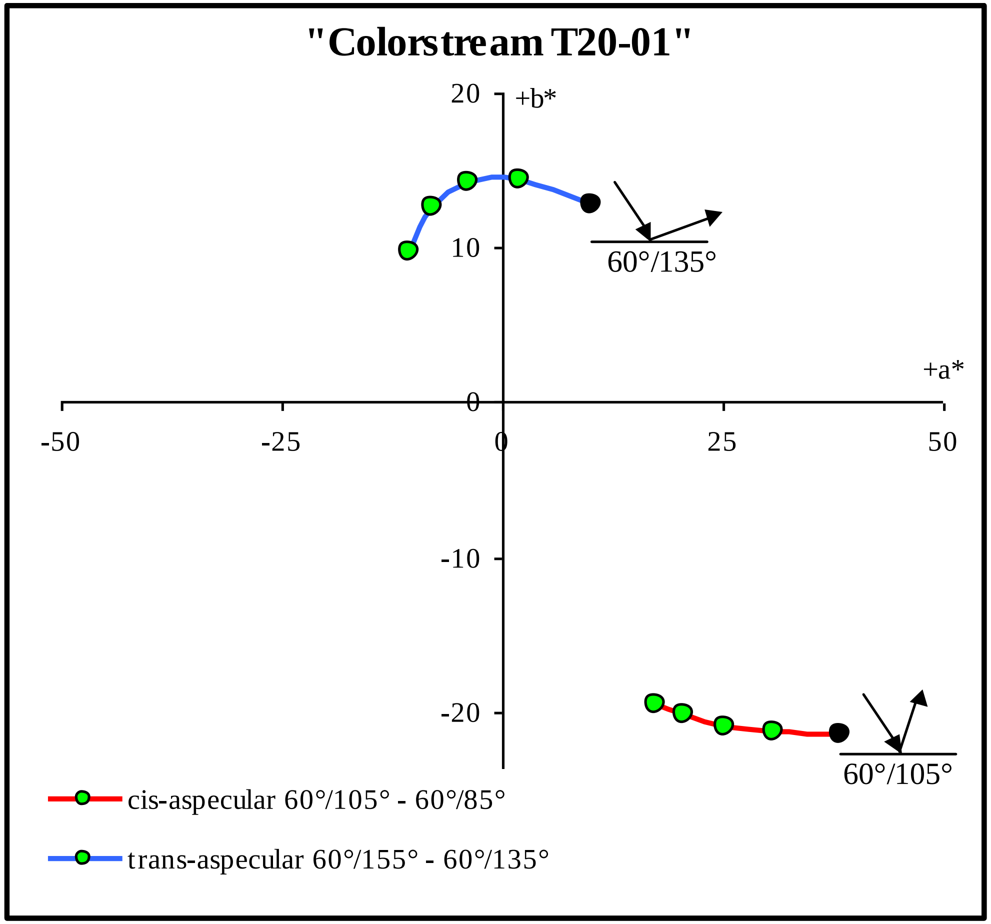
- 1^{st} approximation to recommended notation:
  - Sign criterion
  - Cis vs. trans geometries
  - Examples:
    - 45ºx:150º
    - 45ºx:135º (spec)
    - 45ºx:120º
    - 45ºx:110º



Measurement geometries

- 1st approximation to recommended notation:



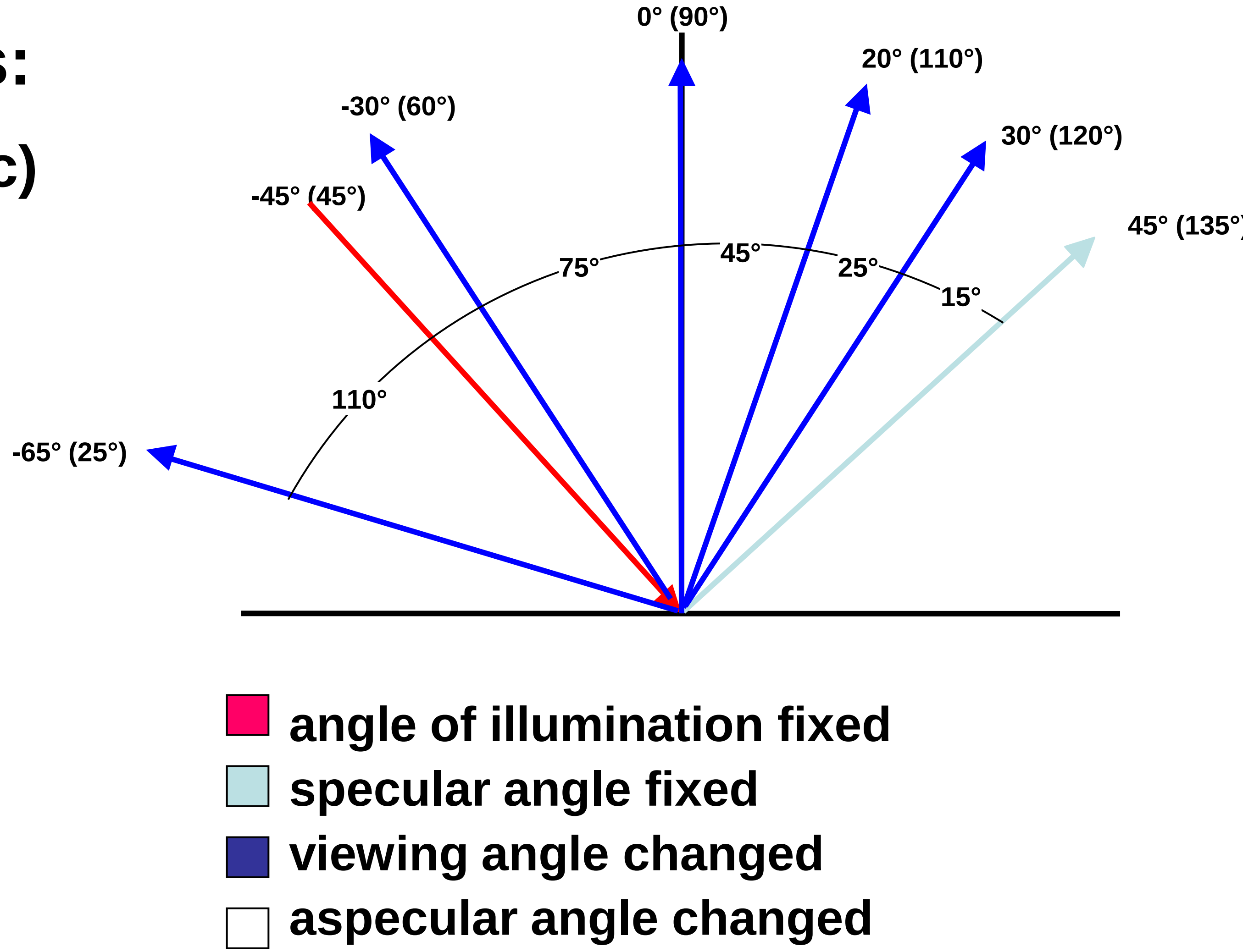


Measurement geometries

- 2nd approximation to recommended notation:
  - Aspecular lines:
    - Constant illumination angle
    - Variable aspecular angle
  - Interference lines:
    - Variable illumination angle
    - Constant aspecular angle, with sign criterion
  - In vs. out of incidence plane

Measurement geometries

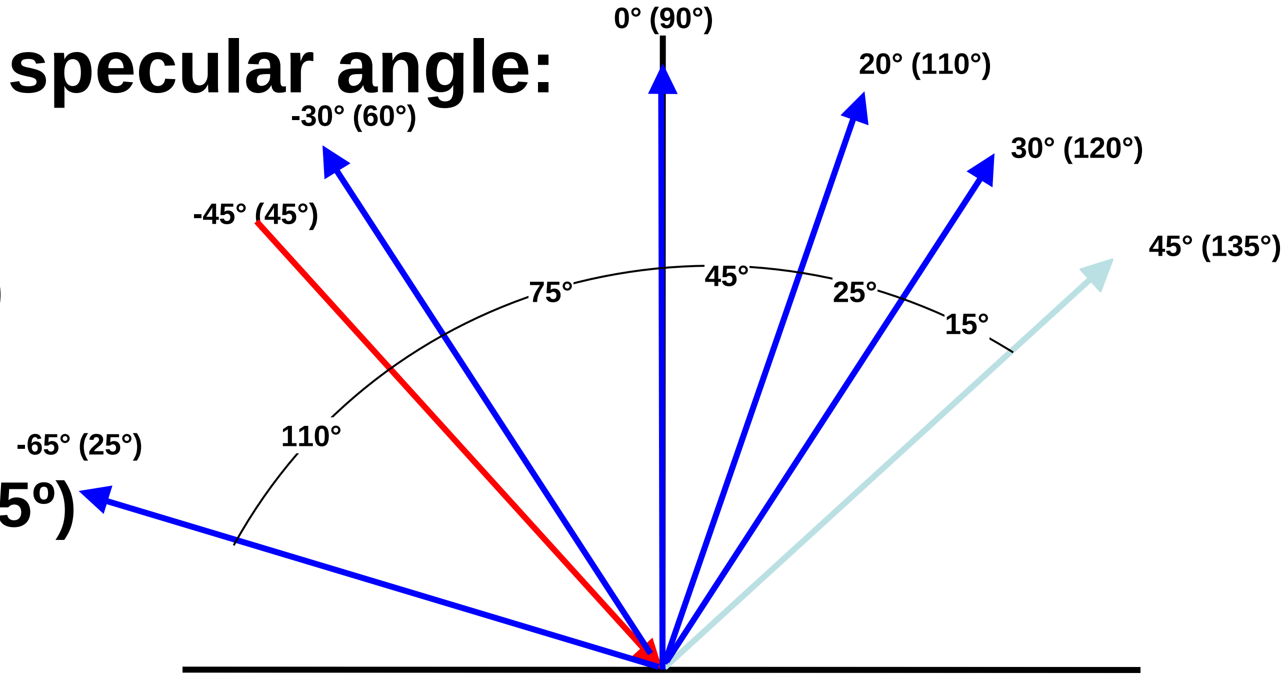
- Aspecular lines:
  - 45ºx:135º (spec)
  - 45ºx:120º
  - 45ºx:110º
  - 45ºx:90º
  - 45ºx:60º
  - 45ºx:25º



Measurement geometries

- From normal and specular angle:
  - 45ºx:135º (spec)
    - = 45º:-45º (as 0º)
  - 45ºx:120º
    - = 45º:-30º (as +15º)
  - 45ºx:110º
    - = 45º:-20º (as +25º)
  - 45ºx:90º
    - = 45º:0º (as +45º)

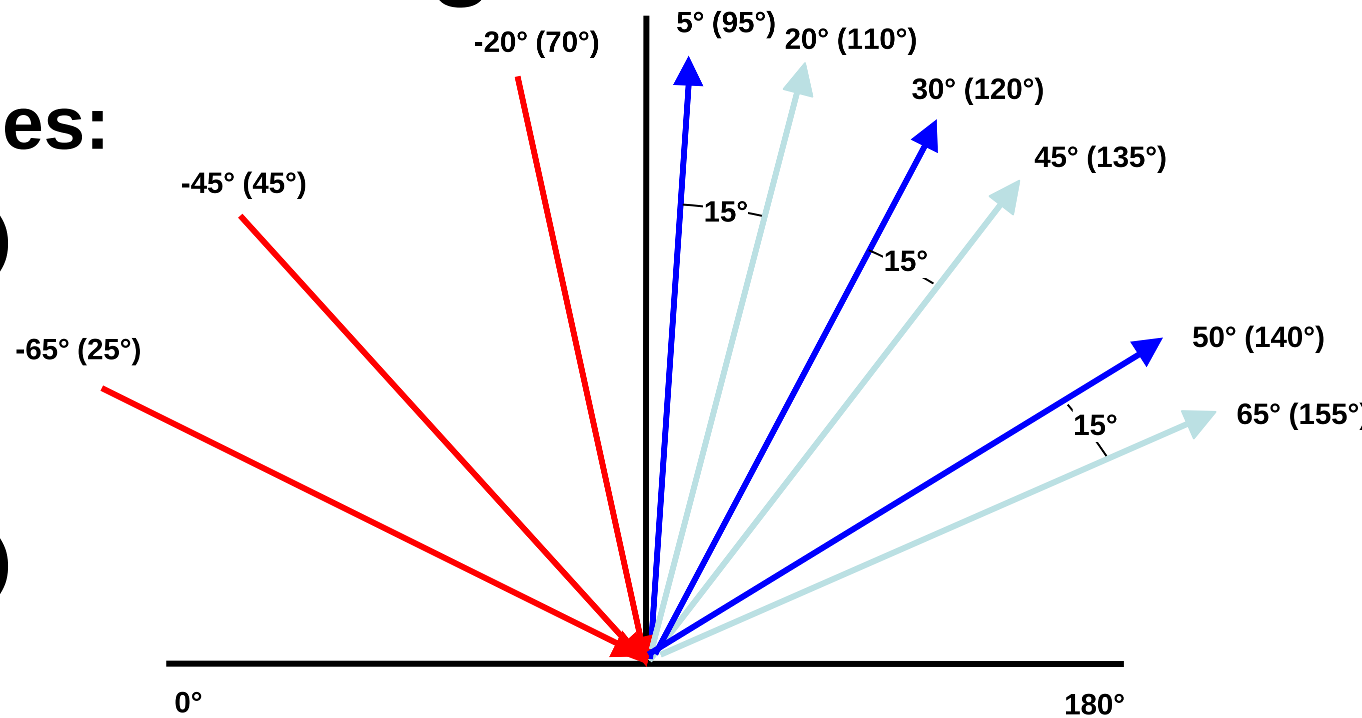
Etc.



angle of illumination fixed
specular angle fixed
viewing angle changed
aspecular angle changed

Measurement geometries

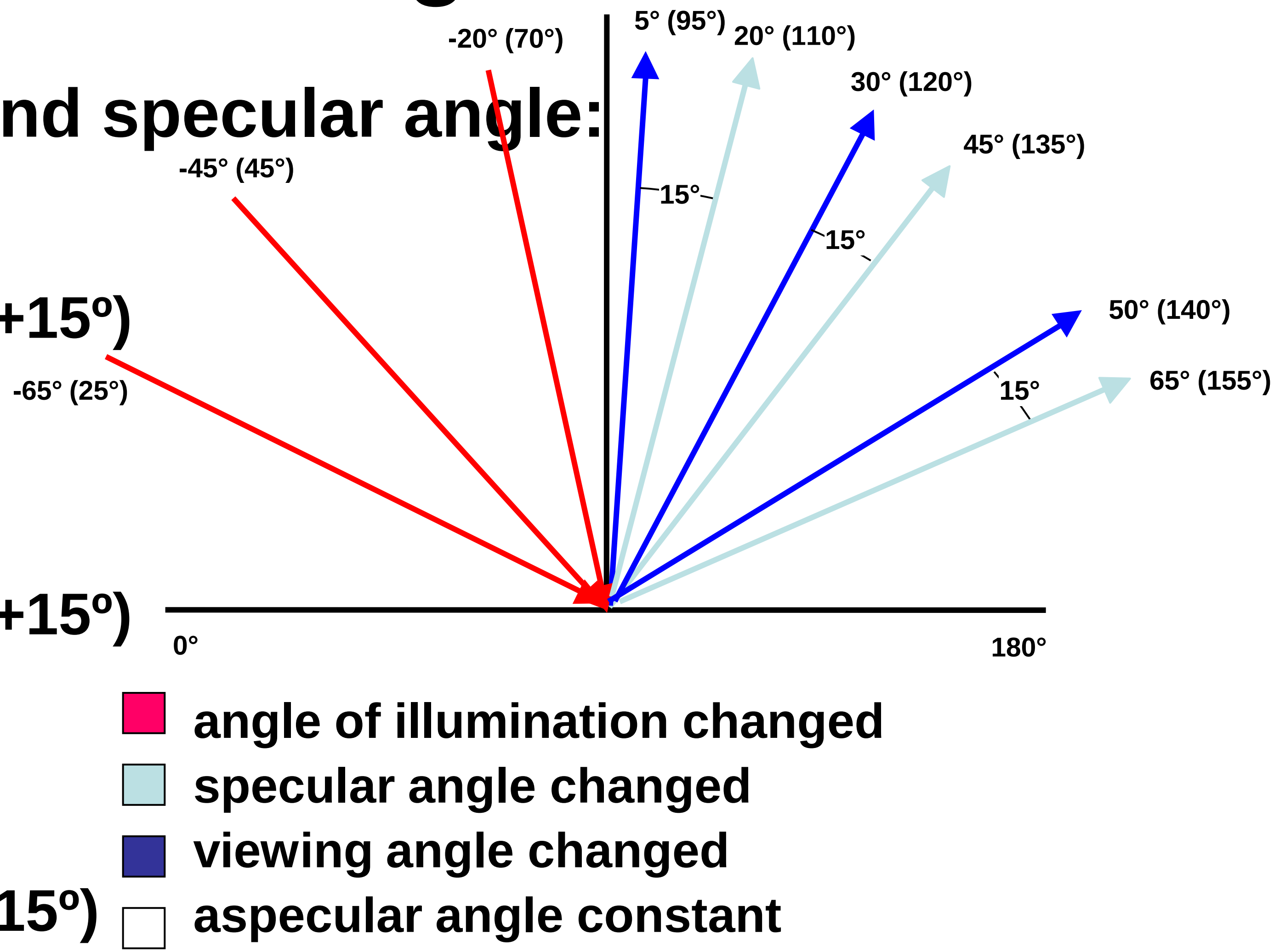
– **Interference lines:**
  – **25º/155º (spec)**
  – **25º/140º (+15º)**
  – **45º/135º (spec)**
  – **45º/120º (+15º)**
  – **70º/110º (spec)**
  – **70º/95º (+15º)**



angle of illumination changed
specular angle changed
viewing angle changed
aspecular angle constant

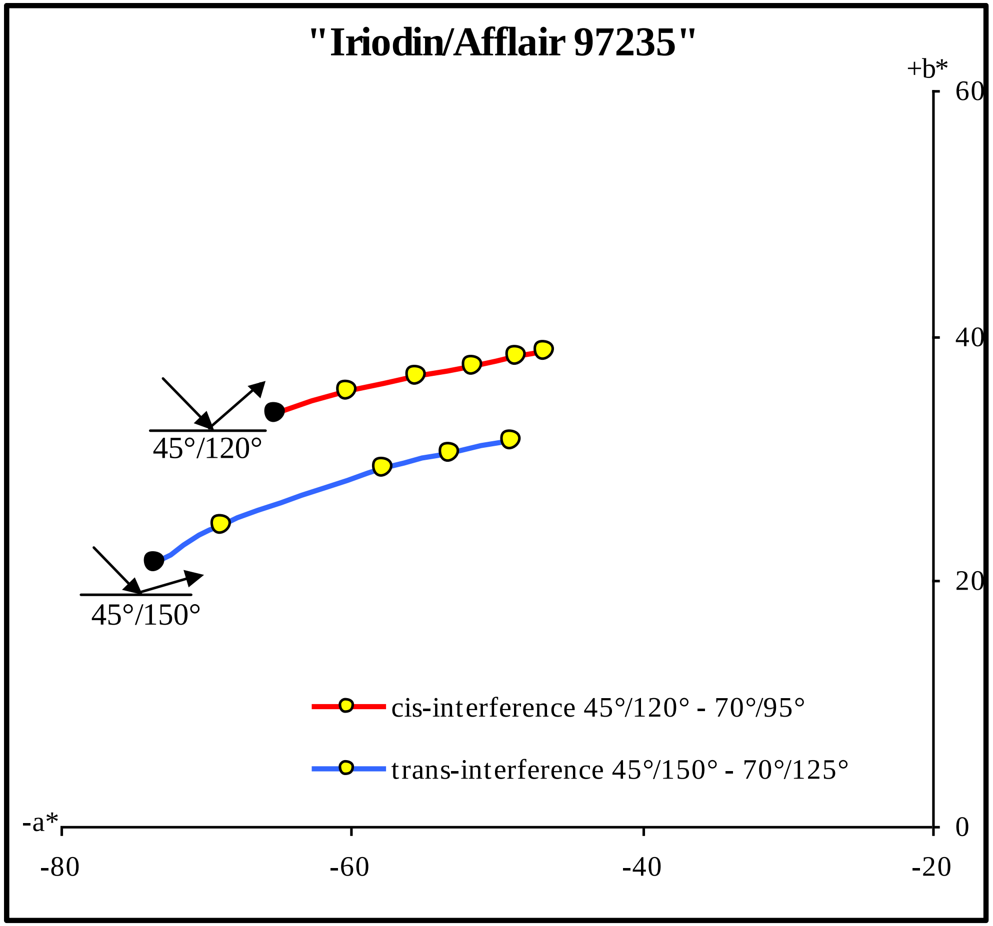
Measurement geometries

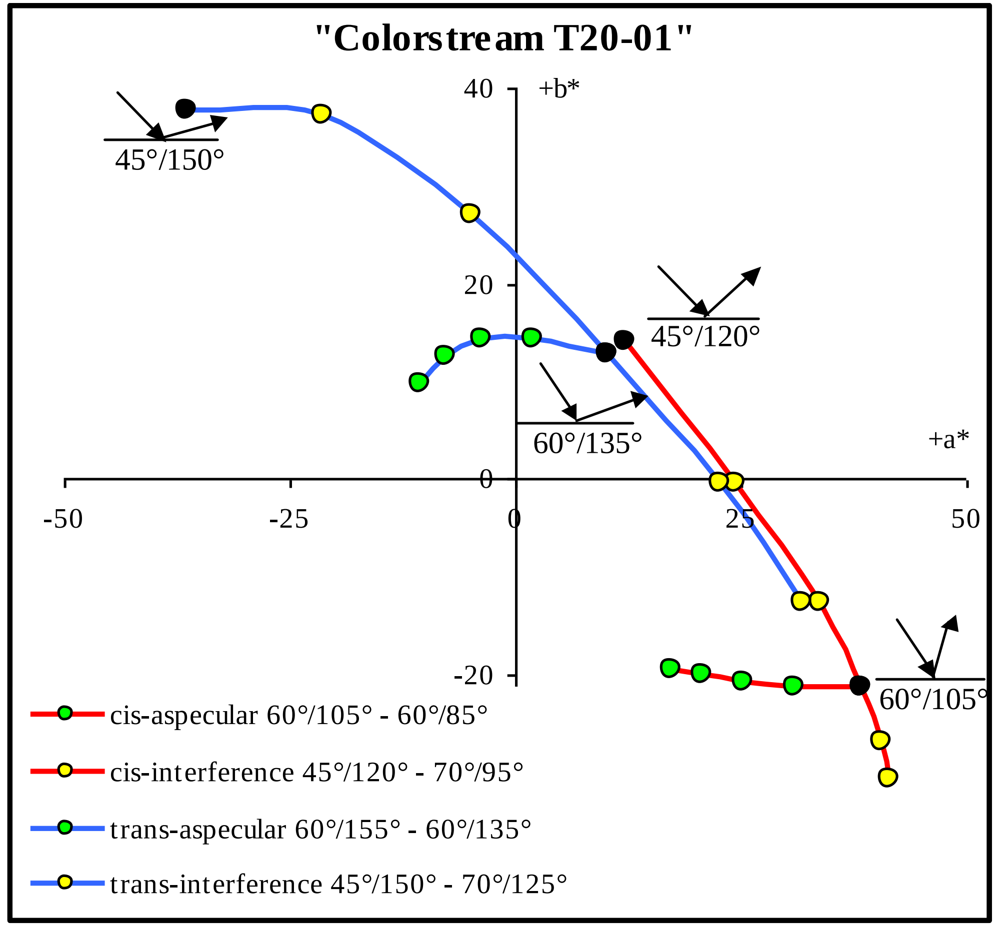
- From normal and specular angle:
  - 25ºx:140º
    = 65º:-50º (as +15º)
    = 65as15
  - 45ºx:120º
    = 45º:-30º (as +15º)
    = 45as15
  - 70ºx:95º
    = 20º:-5º (as +15º)
    = 20as15



Measurement geometries

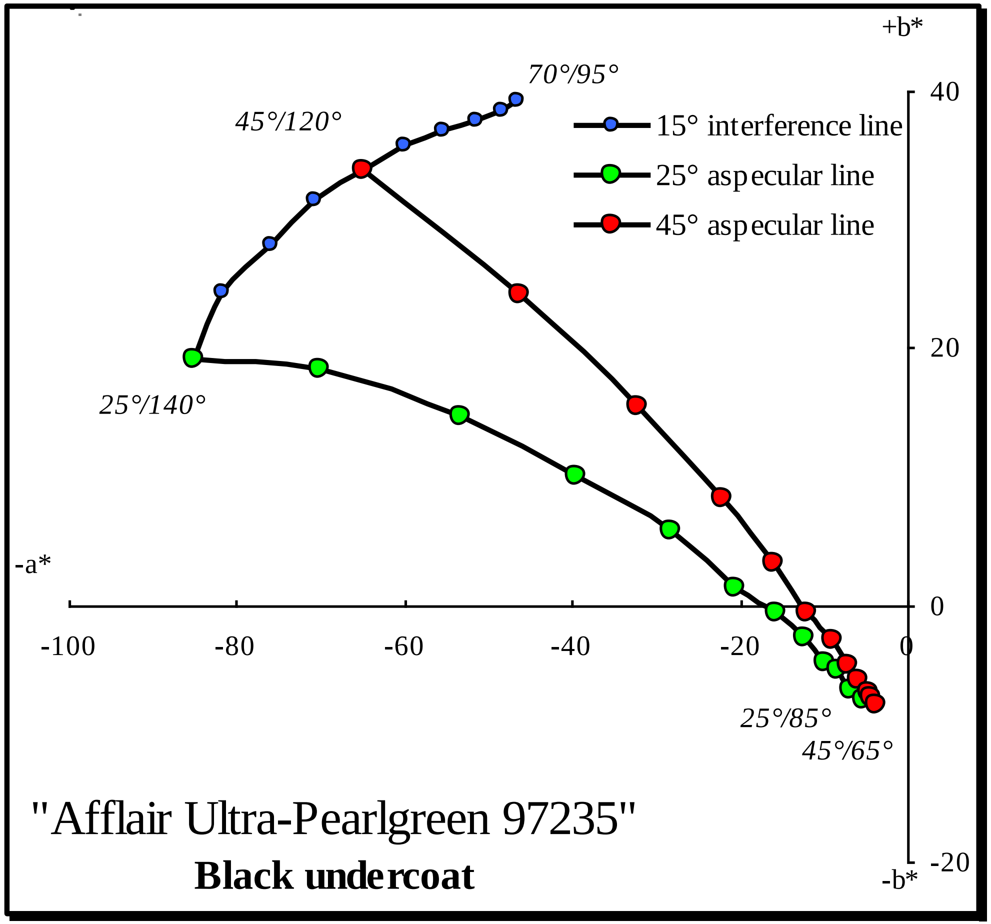
- 2nd approximation to recommended notation:

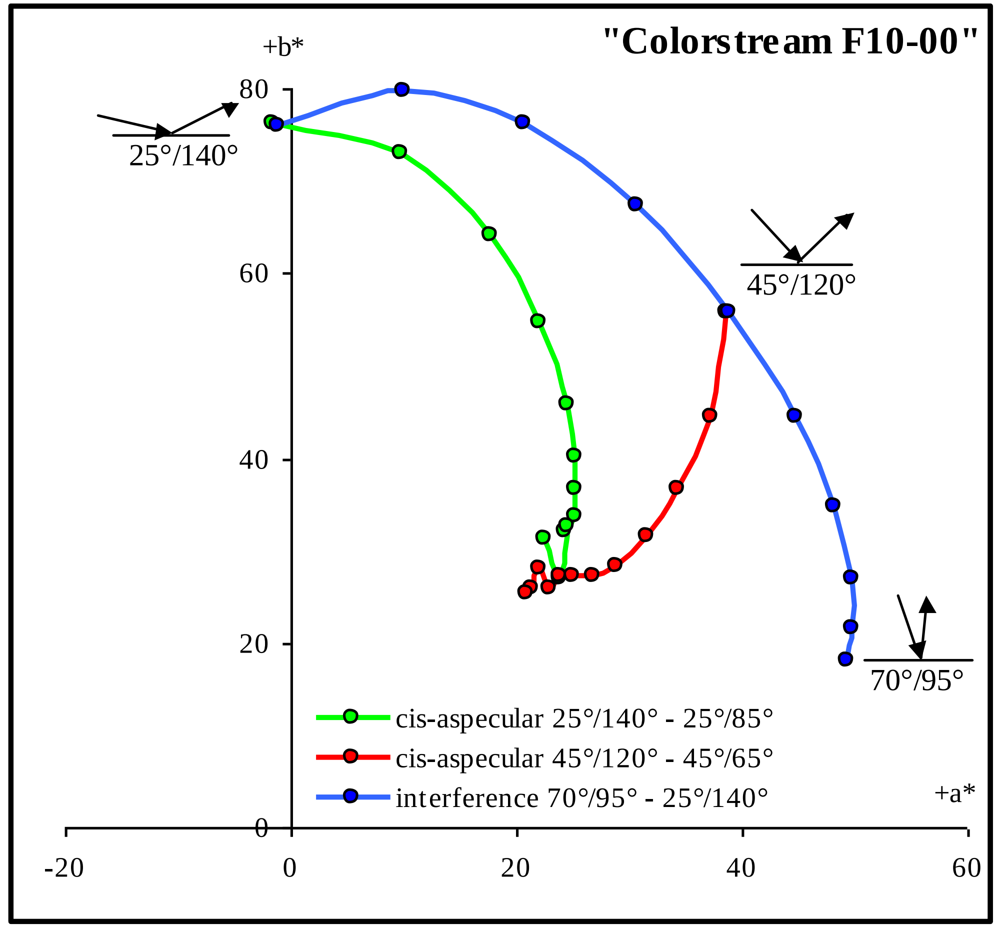




Measurement geometries

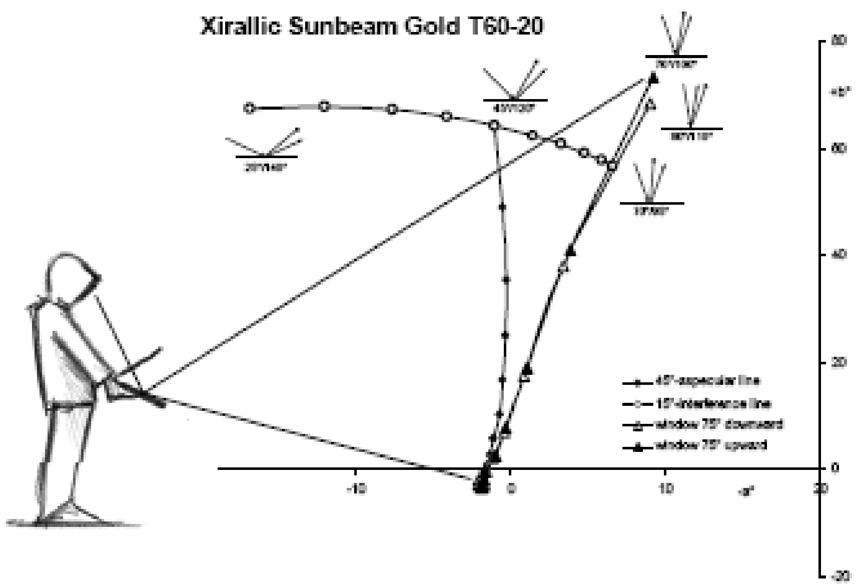
- **More examples:**

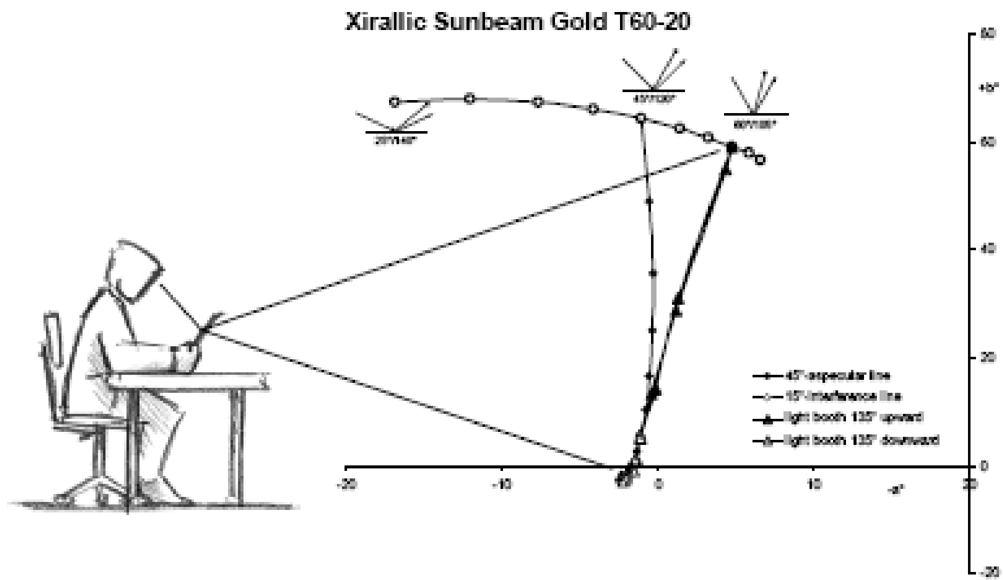




Recommendations for observation

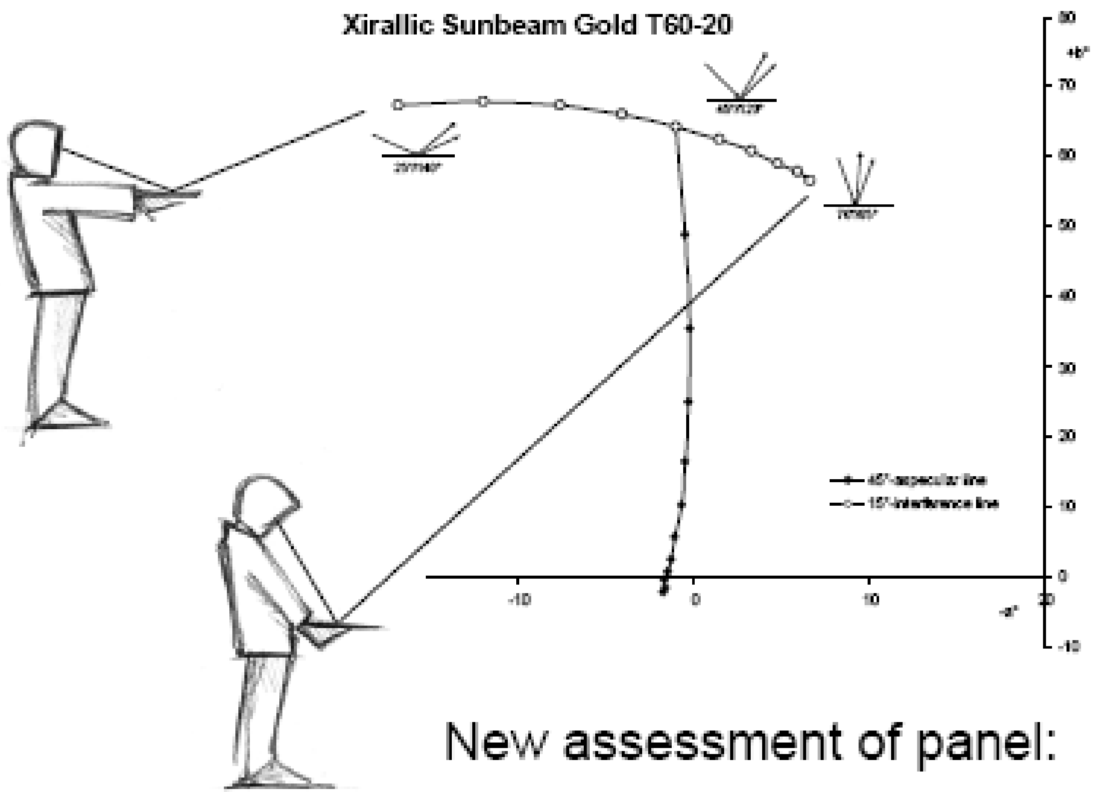
- **Along aspecular lines:**





Recommendations for observation

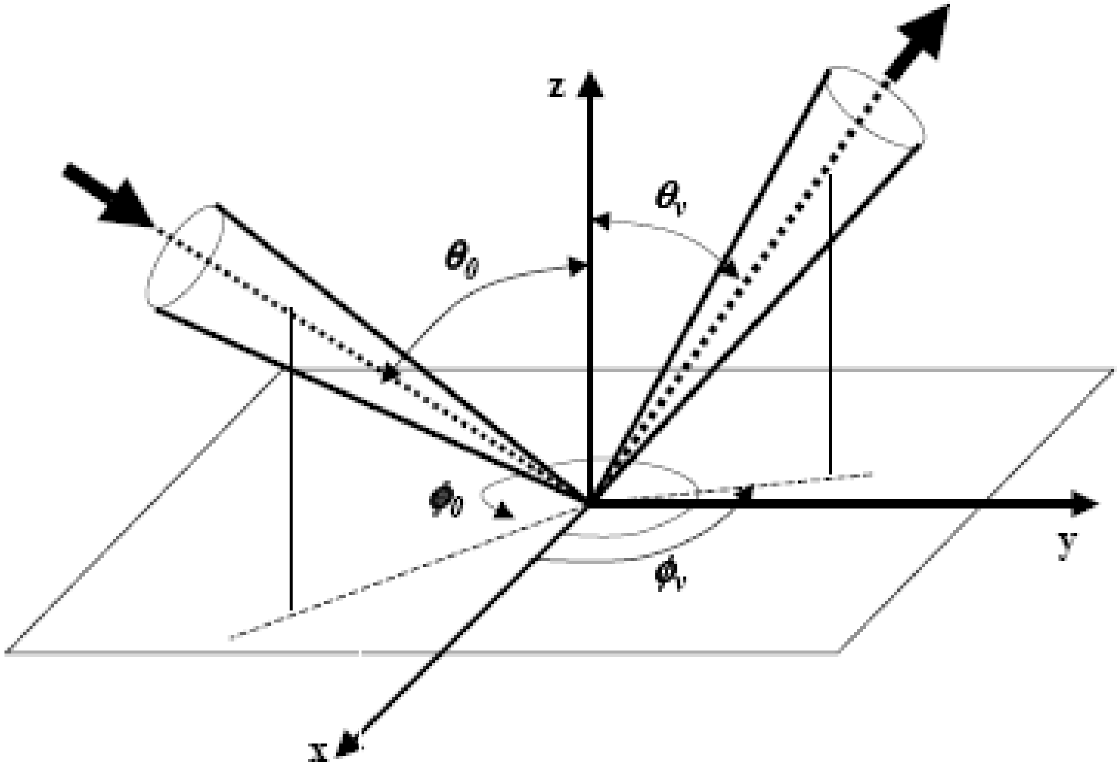
- **Along interference lines:**



New assessment of panel:
Moving panel parallel up and down.

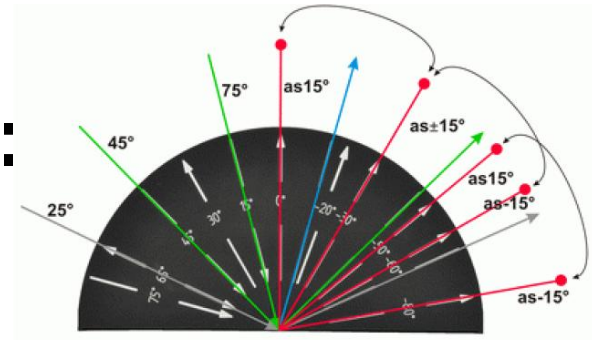
Measurement geometries

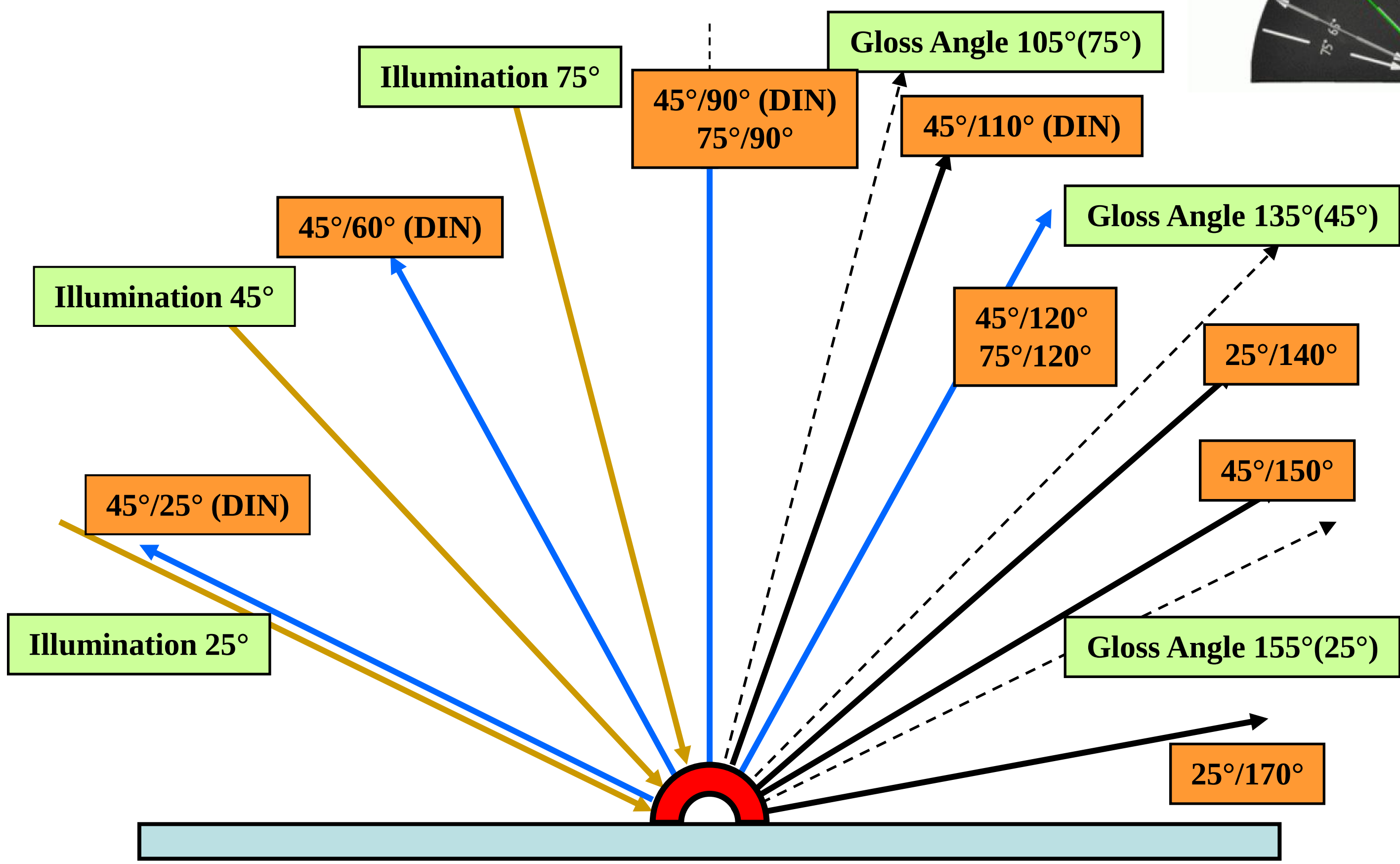
- In vs. Out of incidence plane:
  - 45as-15az0º = 45ºx:150º in plane
  - 45as-15az90,
    out of plane
  - 50.1as-15az33.4,
    out of plane
  - Etc.



Measurement geometries

- **Exercise with Gonio-Vision-Box:**



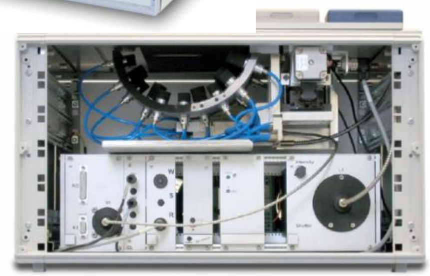


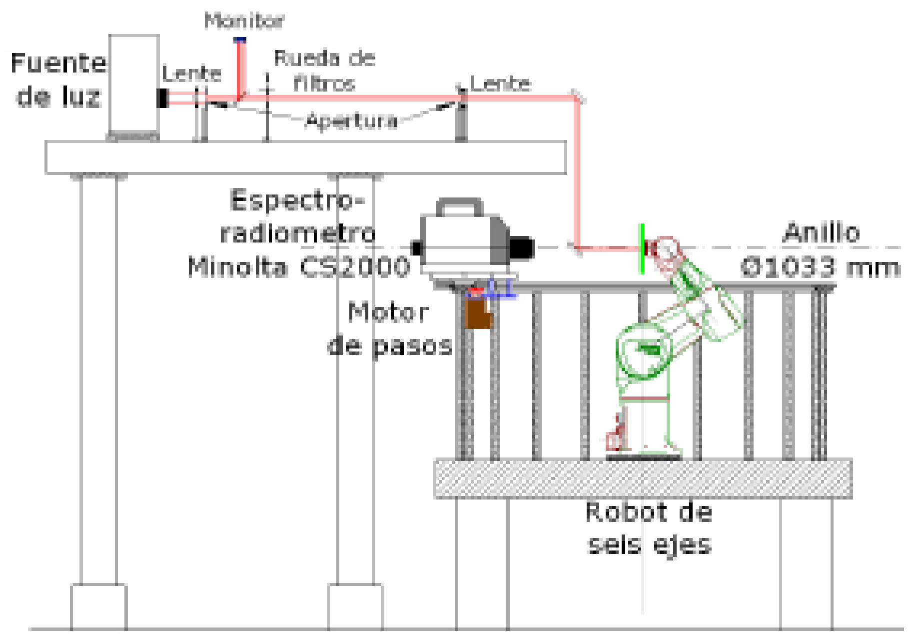
International standards

- CIE 15:2004, directional geometries
- ASTM E2539-08 ; ASTM E2175-08
- ASTM E2194-09 ; ASTM E284-09a
- ASTM E2387-05 ; ASTM E1767-04

Standards	ASTM interference line						ASTM/DIN aspecular line			
illumination angle	25º	25º	45º	45º	75º	75º	45º	45º	45º	45º
observation angle	170º (-15º)	140º (+15º)	150º (-15º)	120º (+15º)	120º (-15º)	90º (+15º)	110º (+25º)	90º (+45º)	60º (+75º)	25º (+110º)

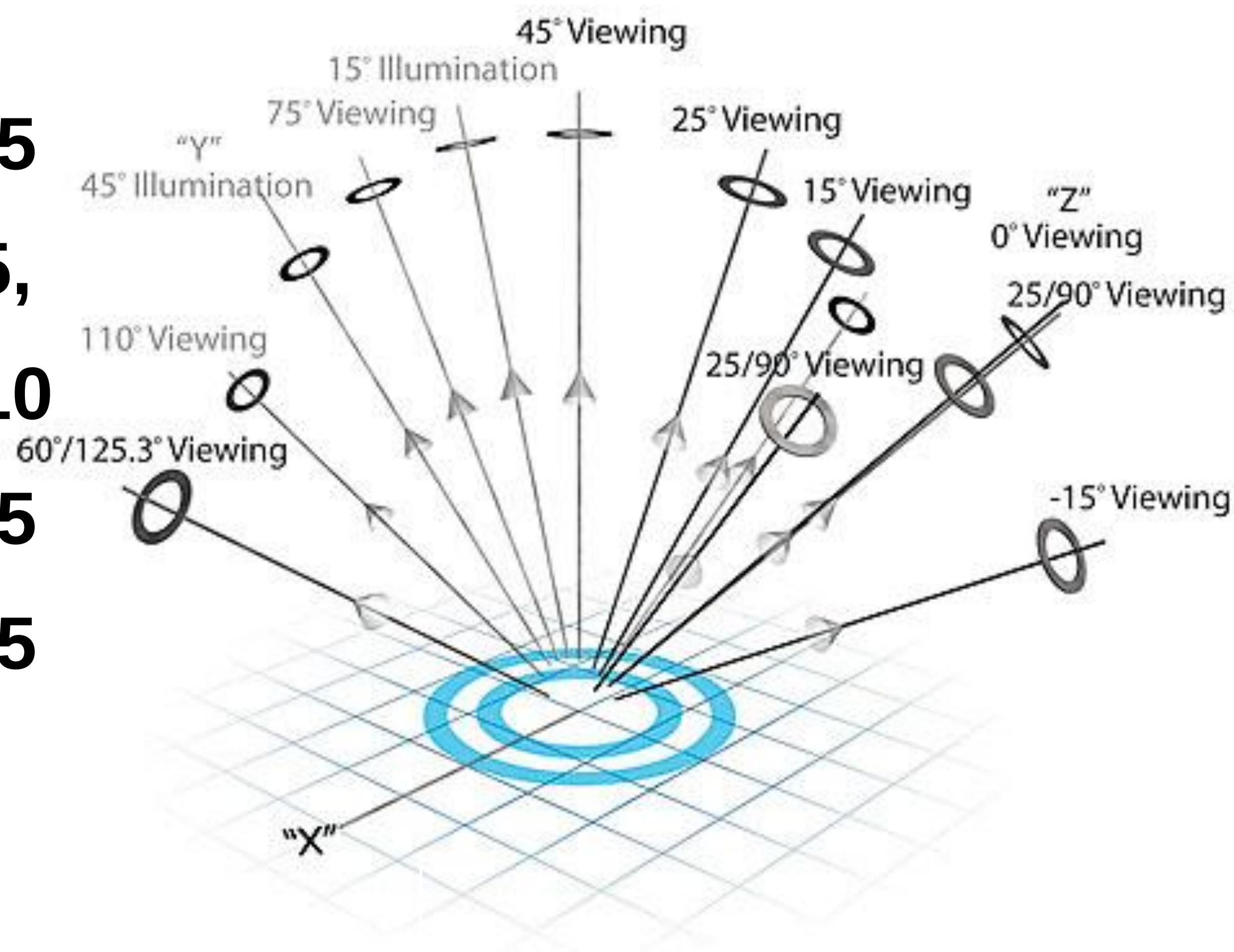
Multi-gonio-spectrophotometers





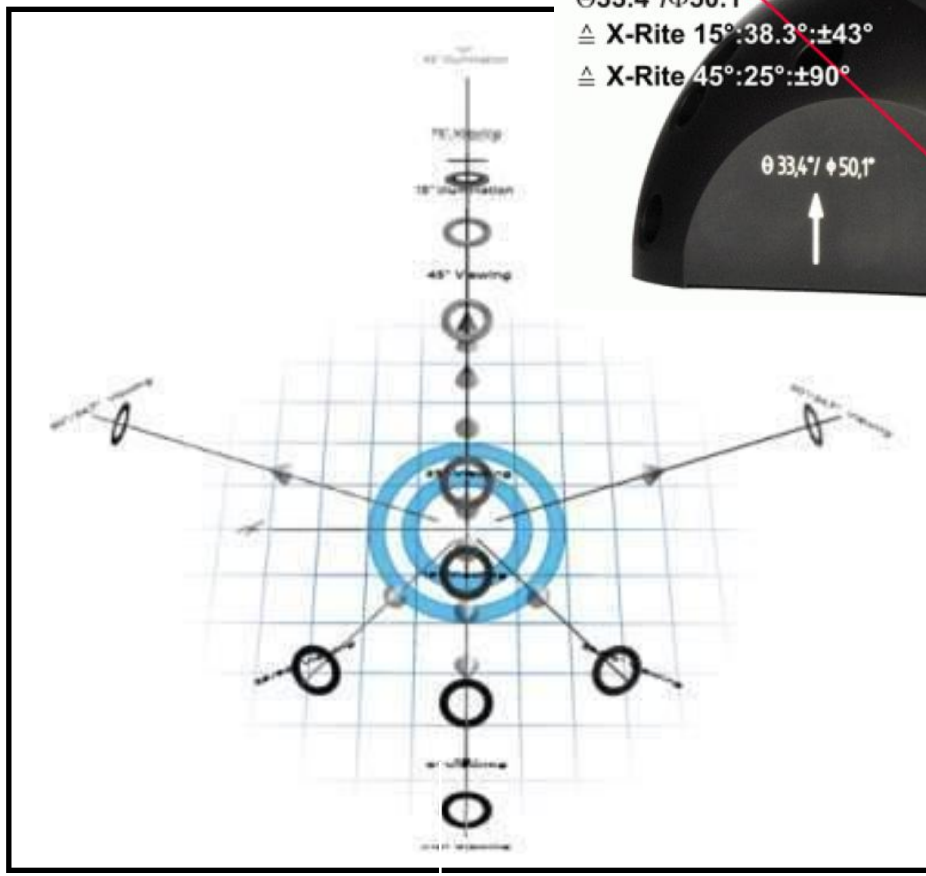
X-Rite MA98

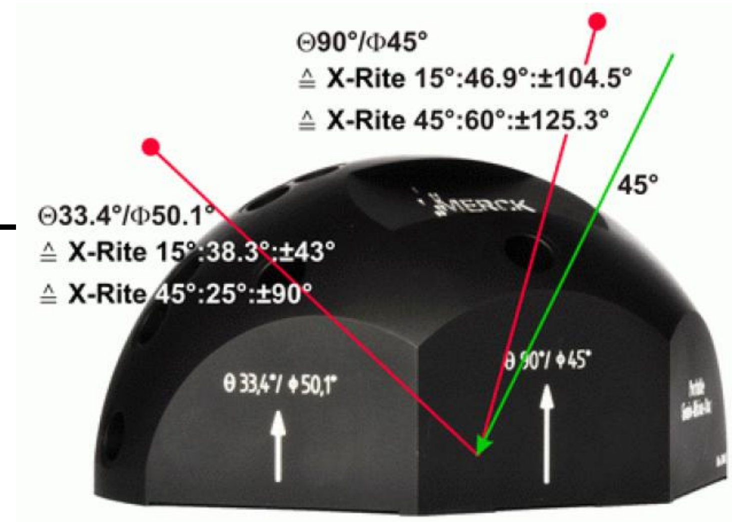
- In-plane geom.:
  - 45as-15 , 45as15
  - 45as25 , 45as45,
  - 45as75 , 45as110
  - 15as-15 , 15as15
  - 15as-45 , 15as45
  - 15as80



X-Rite MA98

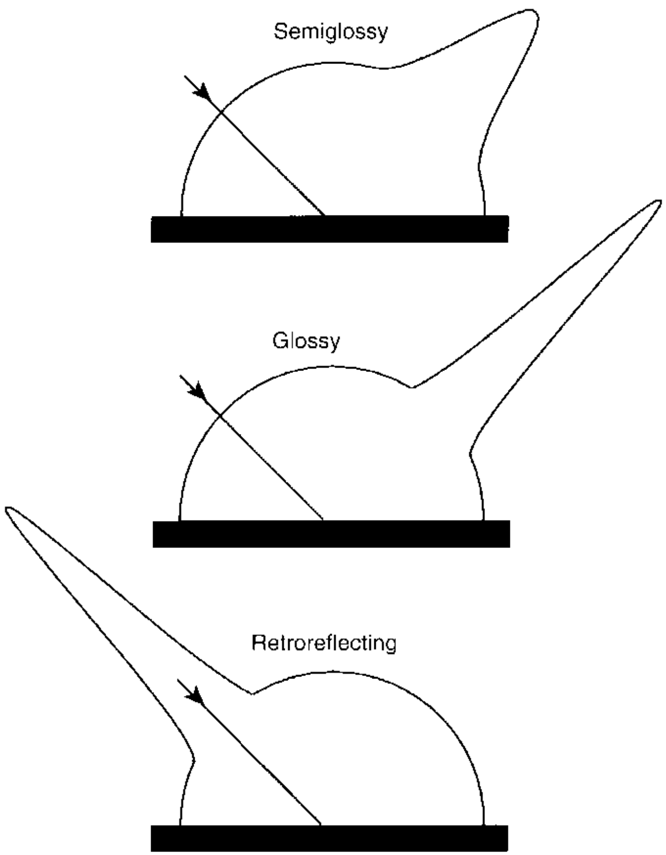
- **Out-of-plane geom.:**
  - 45as25az90
  - 45as25az-90
  - 45as60az125.3
  - 45as60az-125.3
  - 15as38.5az43
  - 15as38.5az-43
  - 15as46.9az104.5
  - 15as46.9az-104.5

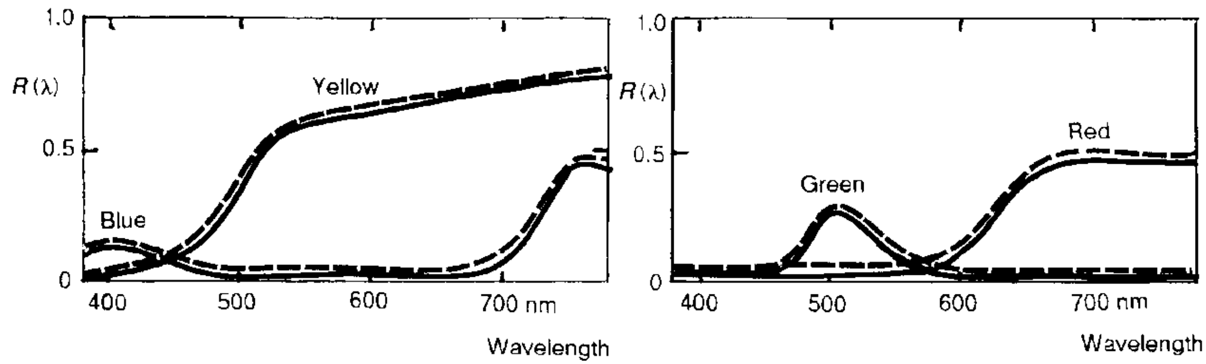


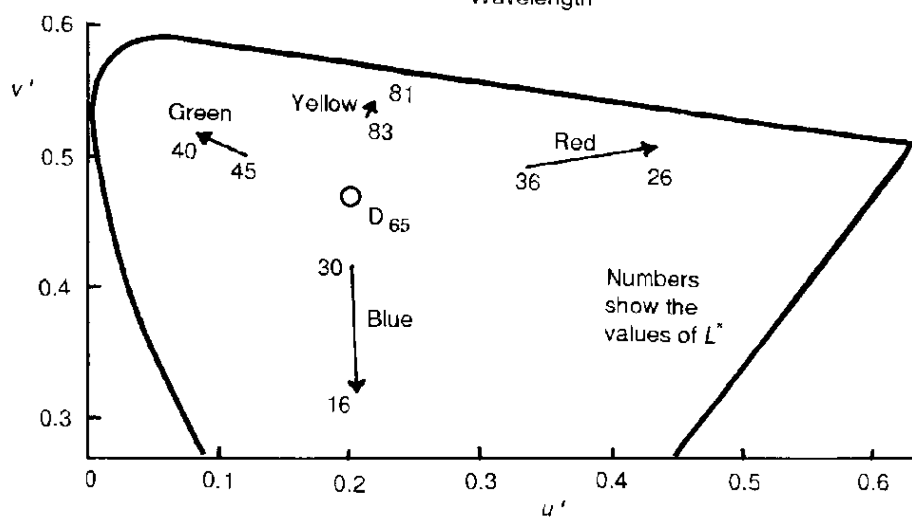


Only chromaticity changes?

- **Lightness changes too: spinc vs. spex in d:8**



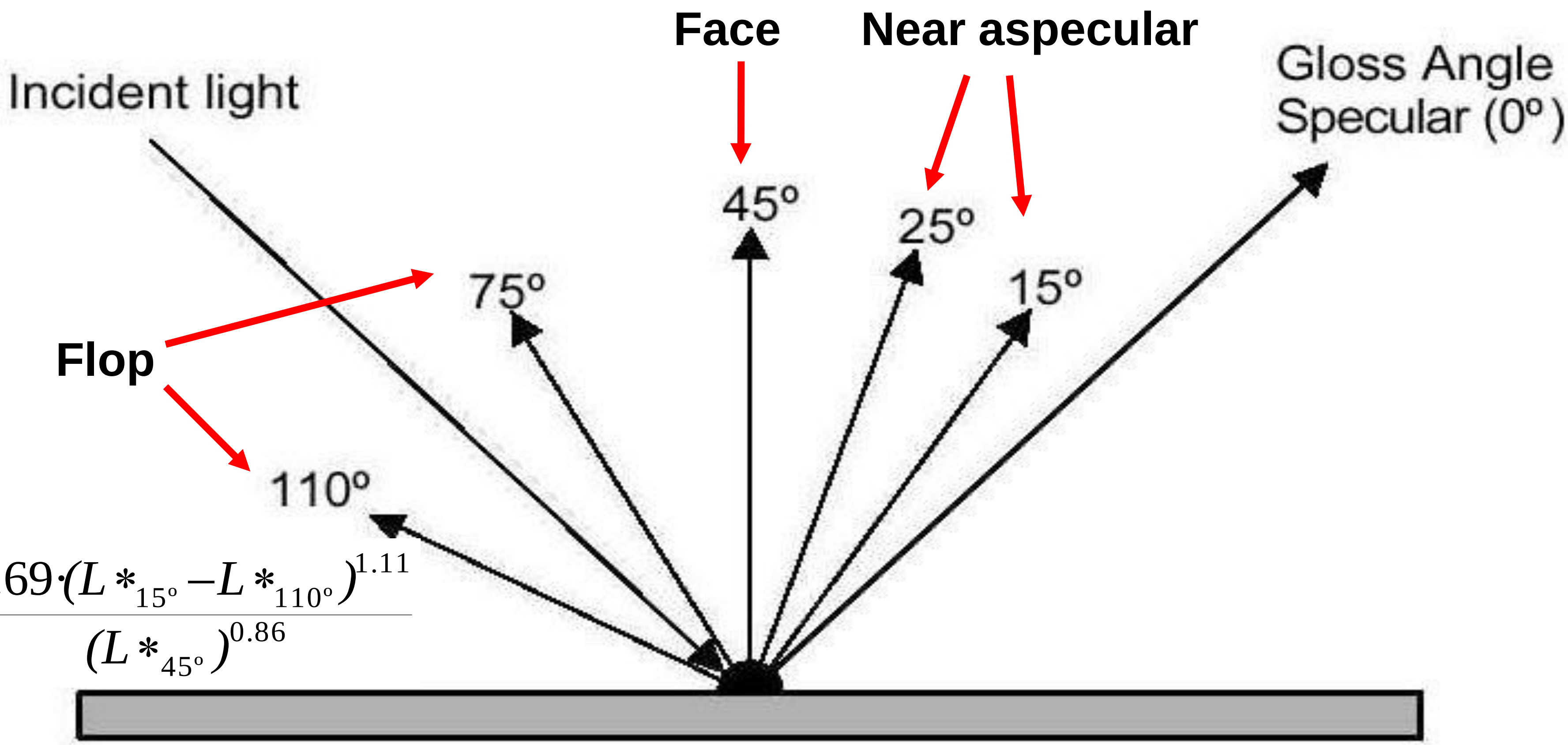




	ΔE^*_{ab}	ΔE^*_{uv}
Yellow	6	4
Green	16	11
Red	18	19
Blue	18	15

Only chromaticity changes?

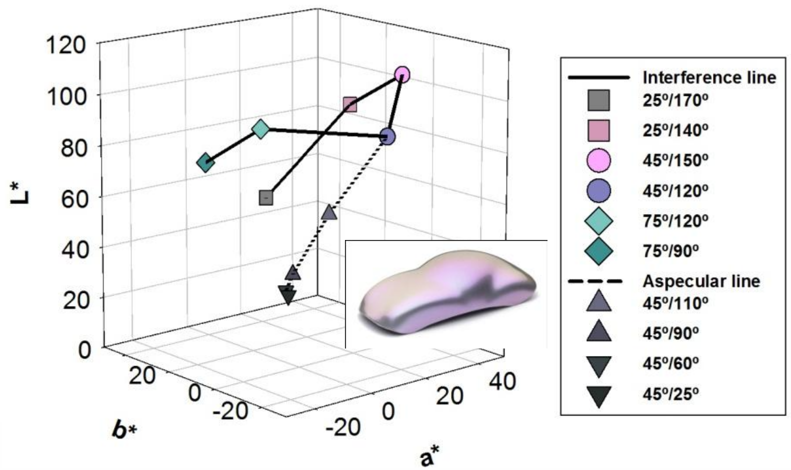
- **Lightness changes too**

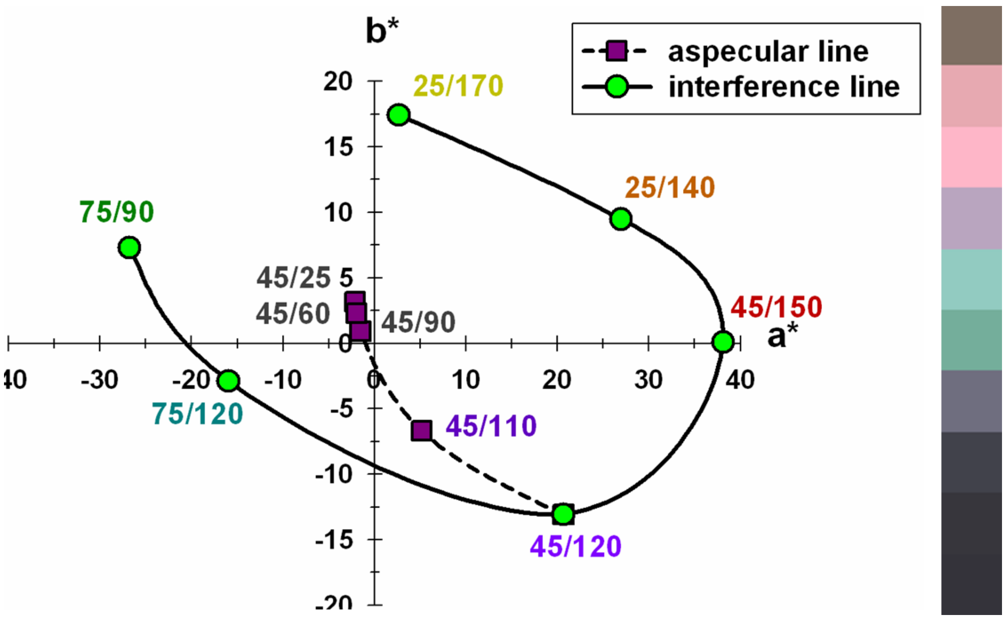


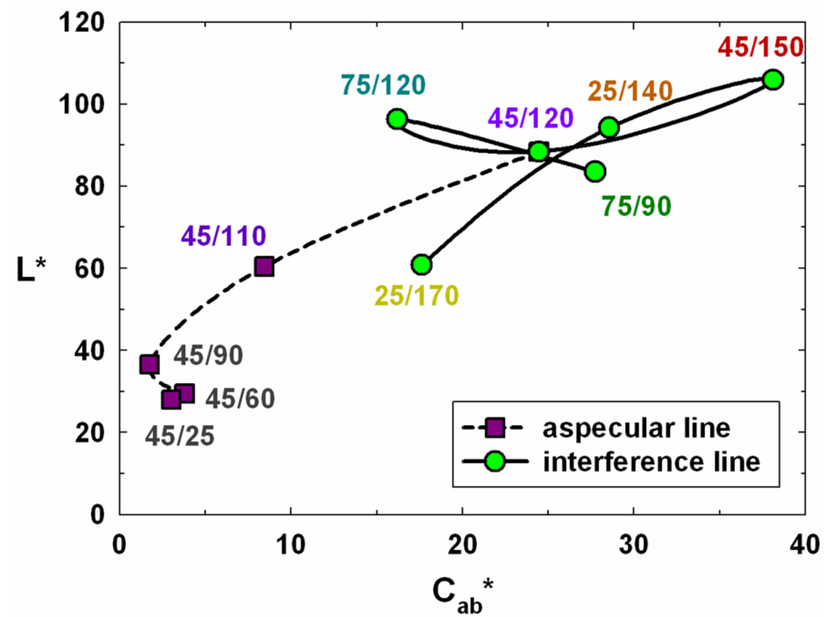
$$Flop = \frac{2.69 \cdot (L*_{15^{o}} - L*_{110^{o}})^{1.11}}{(L*_{45^{o}})^{0.86}}$$

Only chromaticity changes?

- **Lightness changes too:**
  - **Sample: Colorstream T20-02 Arctic Fire Exterior**

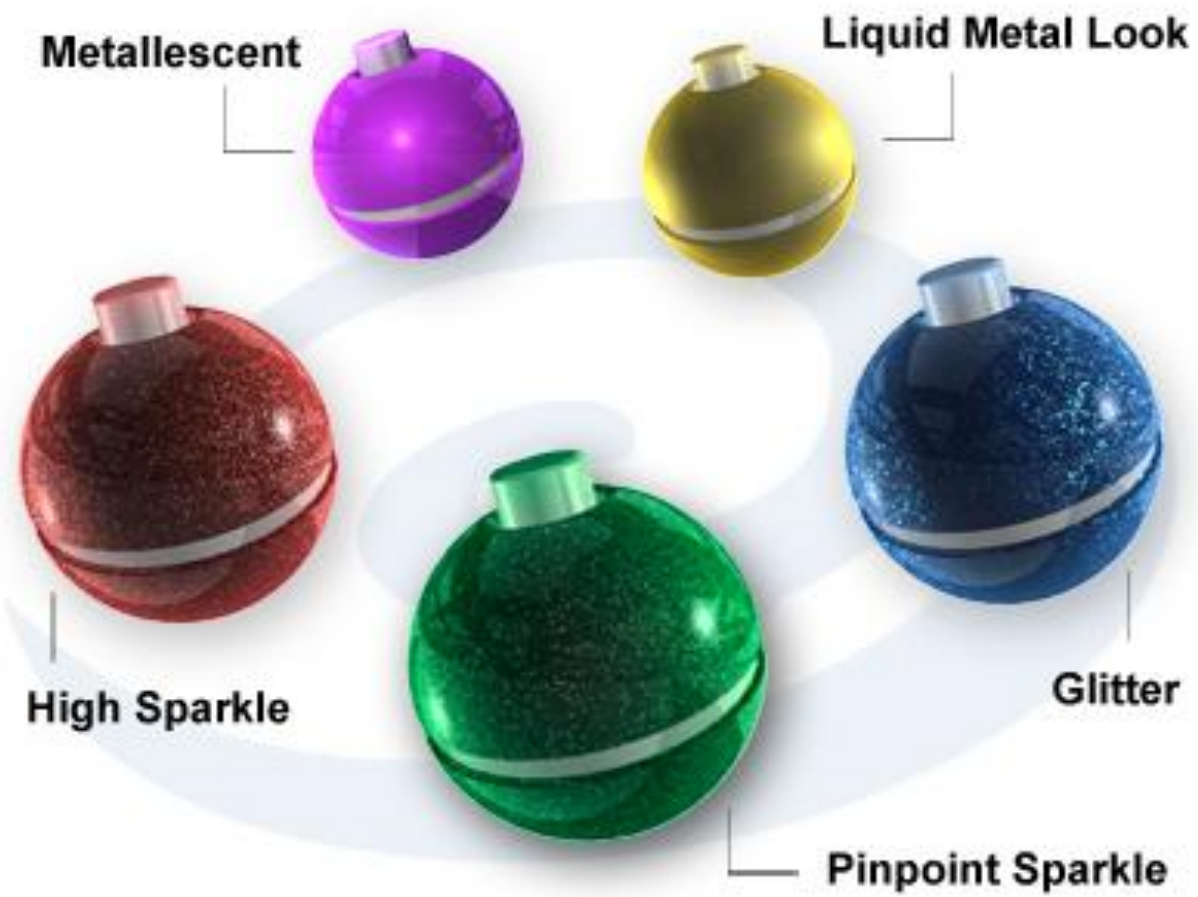






Texture changes in goniochromism

- **Sparkle (glitter) and graininess:**
  - From many small, discrete reflecting elements

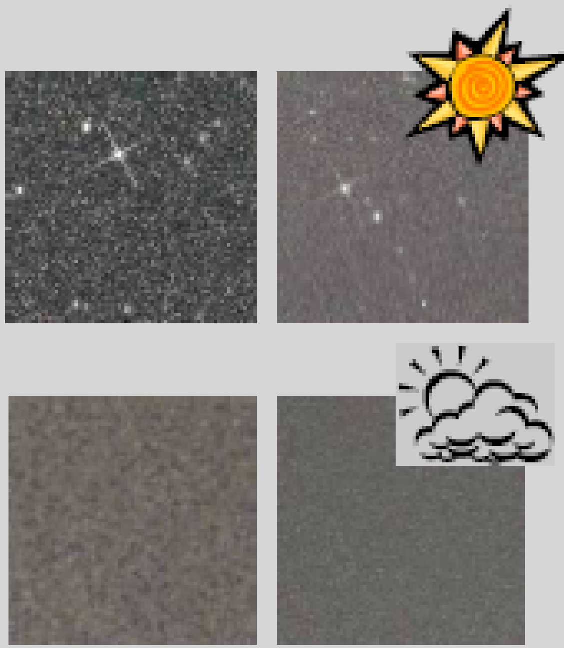


- **Depending on:**
  - Lighting design
  - Viewing distance

Texture changes in goniochromism

- **Sparkle vs. graininess: illumination conditions**

Appearance of effect finishes depends on illumination conditions:



Sunny sky: Direct illumination

- Color starts to sparkle

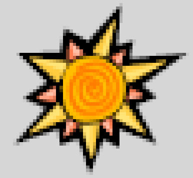
Cloudy sky: Diffused illumination

- Fine versus grainy pattern

Texture changes in goniochromism

- **Sparkle vs. graininess: illumination conditions**

Sparkle: Micro brightness – Glints – Diamonds



Viewing conditions:

- Spotlight ~ direct sun light conditions
- Observation angle critical: Sparkle impression changes with illumination angle

Sparkle is generated by e.g.:

- Reflectivity of the individual effect pigment (alu flakes, mica, Xirallics®)
- Amount of effect pigments
- Size of the aluminum flakes
- Flake orientation → Sparkle 75°

High Sparkle

Low Sparkle

Texture changes in goniochromism

- **Sparkle vs. graininess: viewing conditions**

Graininess:

Texture – Structure – Coarseness – Salt & Pepper 

Viewing conditions:

- Diffused light
- Close observation distance
- Observation angle not important

Potential causes of graininess:

- Flake type – flake size
- Disorientation of flakes
- Agglomeration of particles

High Graininess	Low Graininess

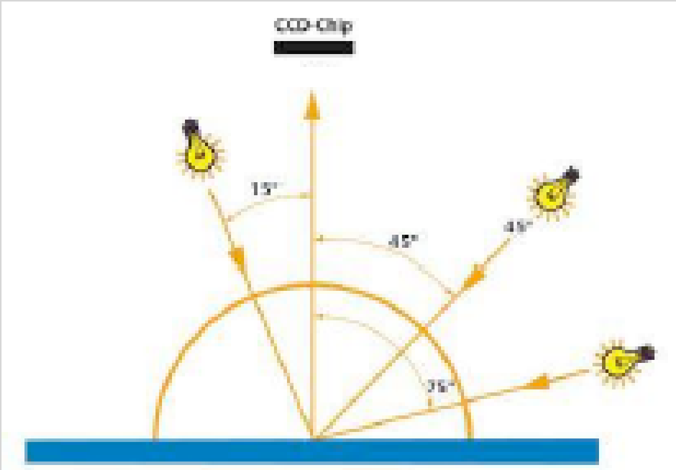
Instrument for measuring texture changes in goniochromism

- **BYK-mac: multi-gonio + mono CCD camera**

- Camera Analysis:
  The spatial resolution of the CCD chip correlates to the spatial resolution of the human eye.

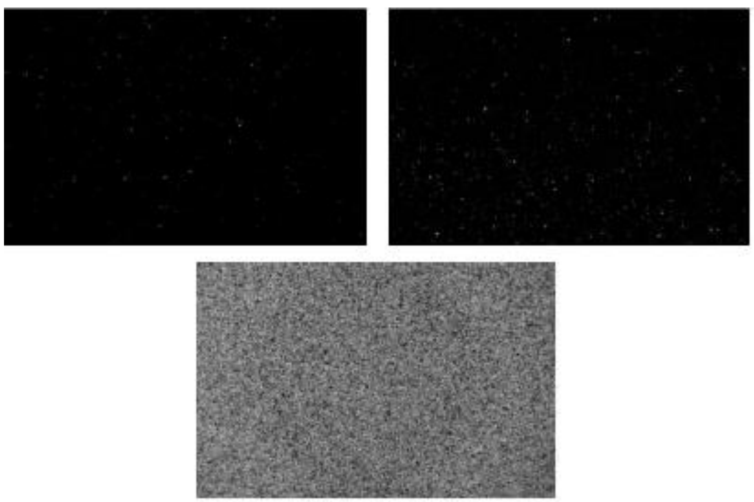
- Camera pictures are taken under different light conditions to simulate sunny sky and cloudy sky.

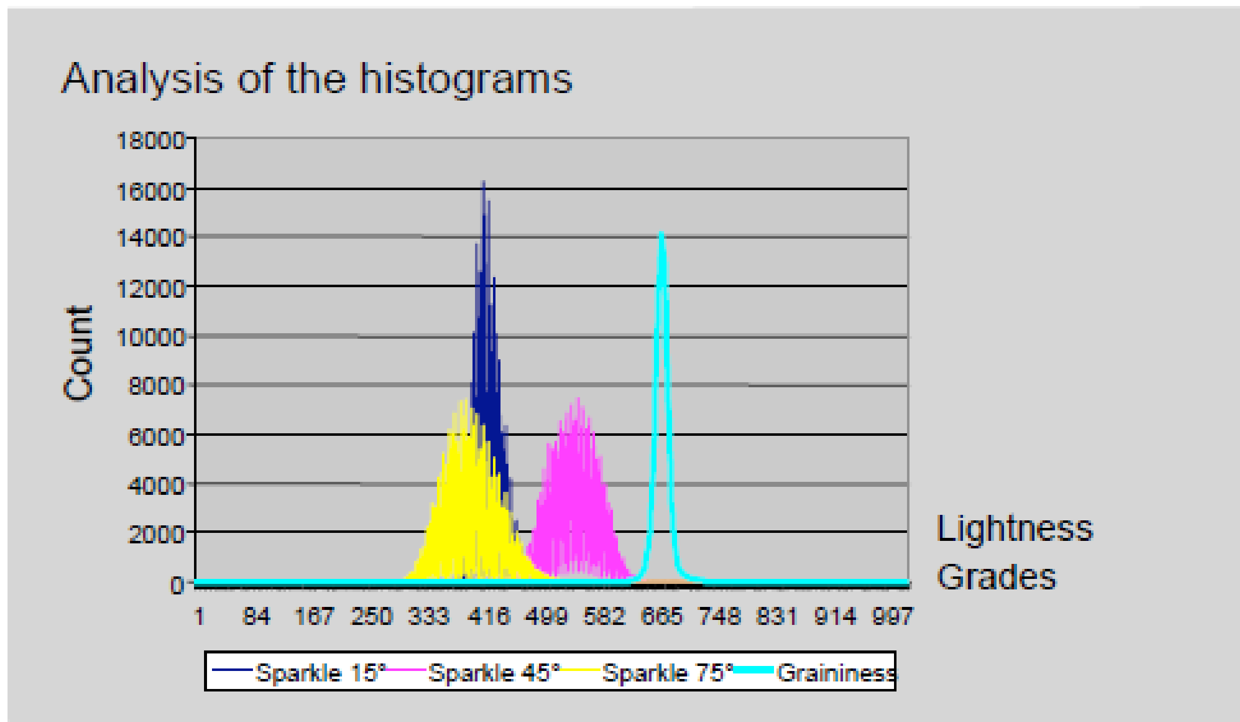
- The sparkling impression is evaluated under 3-illumination angles: 15°- 45°-75°



Instrument for measuring texture changes in goniochromism

- BYK-mac: multi-gonio + mono CCD camera
  - Camera pictures characterize sparkle and graininess
  - Calculation of sparkle and graininess values

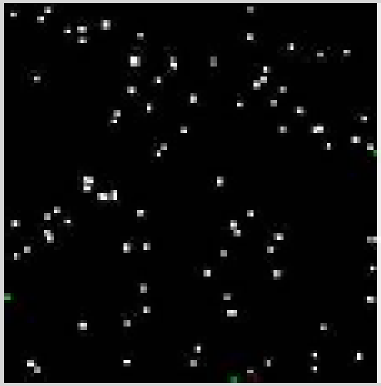




Instrument for measuring texture changes in goniochromism

- **BYK-mac: flake characterization**

Analysis of Sparkle Effect:

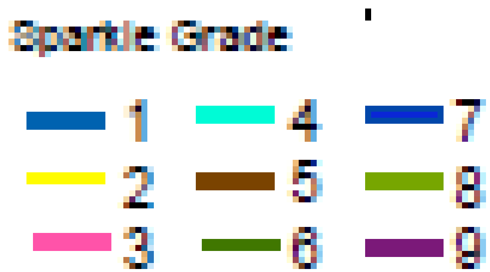


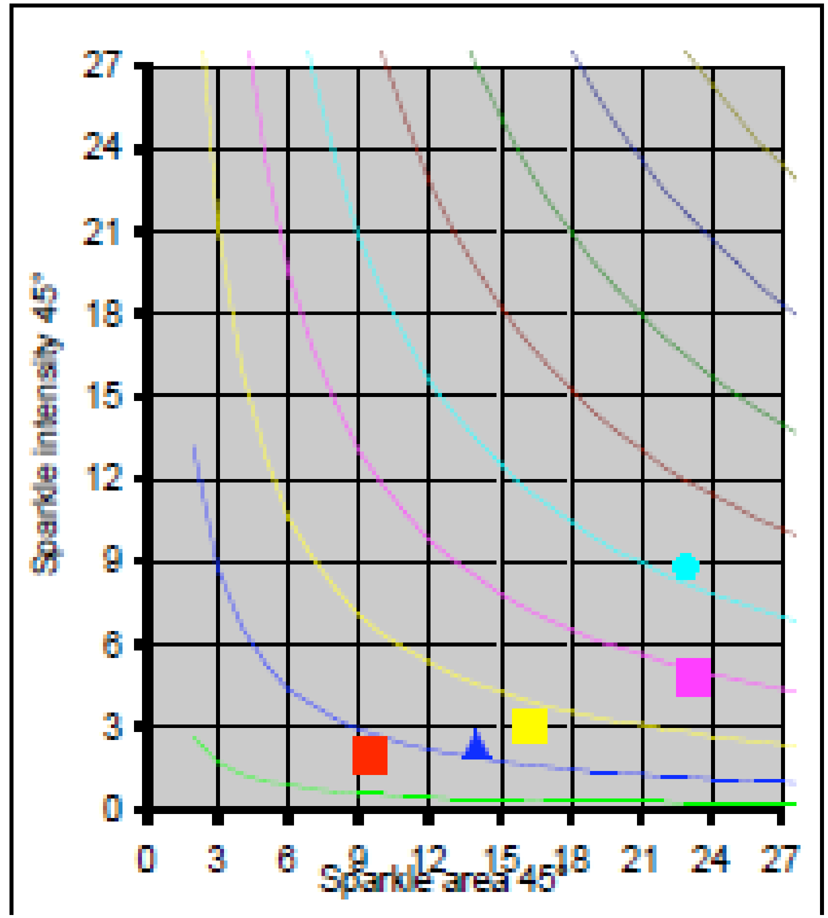
- **Sparkling area** is detected → Not size of the individual effect pigment
- **Sparkling intensity** is measured: How strong is the light flash of the effect pigment
- Total **Sparkle Grade** is determined as a function of Sparkle area and Sparkle intensity

Instrument for measuring texture changes in goniochromism

- BYK-mac: analysis of sparkle effect
  - Sparkle parameters:
  - 1-D: grade
  - 2-D: area – intensity

Sparkle Grade = f (Sa, Si)





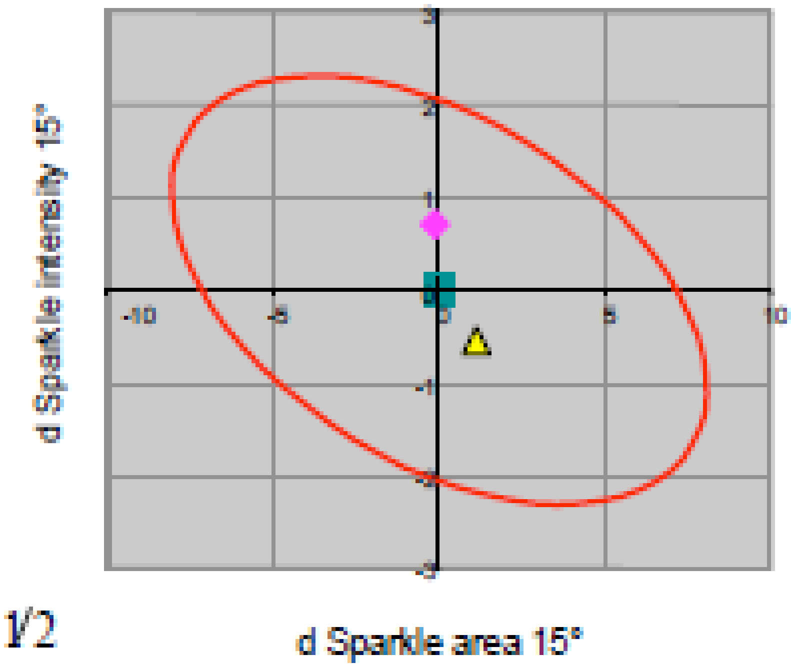
Instrument for measuring texture changes in goniochromism

- **BYK-mac: sparkle tolerance model**

  – **Sparkle differences:**

  ΔS = sample – standard

  For 15º , 45º and 75º deg



$$\Delta S = \left[\left(\frac{\Delta S\_a}{f(Tol\_Gr)} \right)^2 + \left(\frac{\Delta S\_i}{f(Tol\_GF \times Tol\_Gr)} \right)^2 \right]^{1/2}$$

ΔSparkle < Tol_S PASS

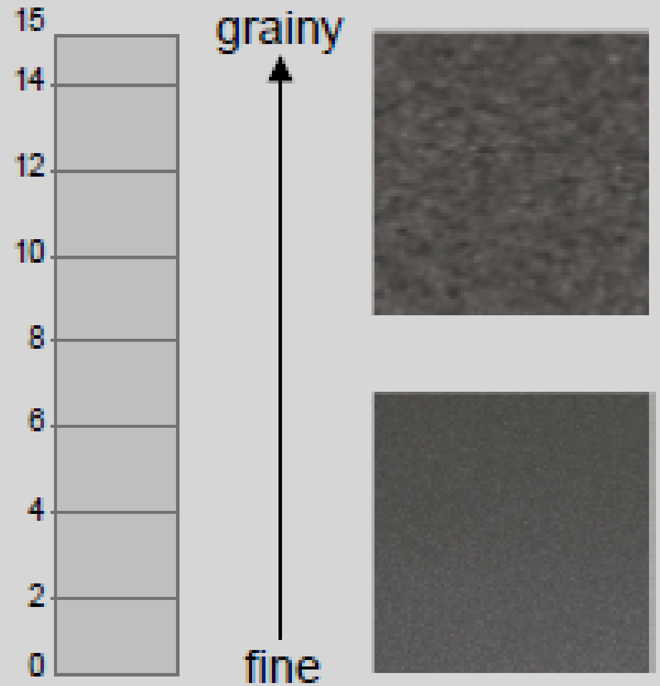
ΔSparkle > Tol_S FAIL

Instrument for measuring texture changes in goniochromism

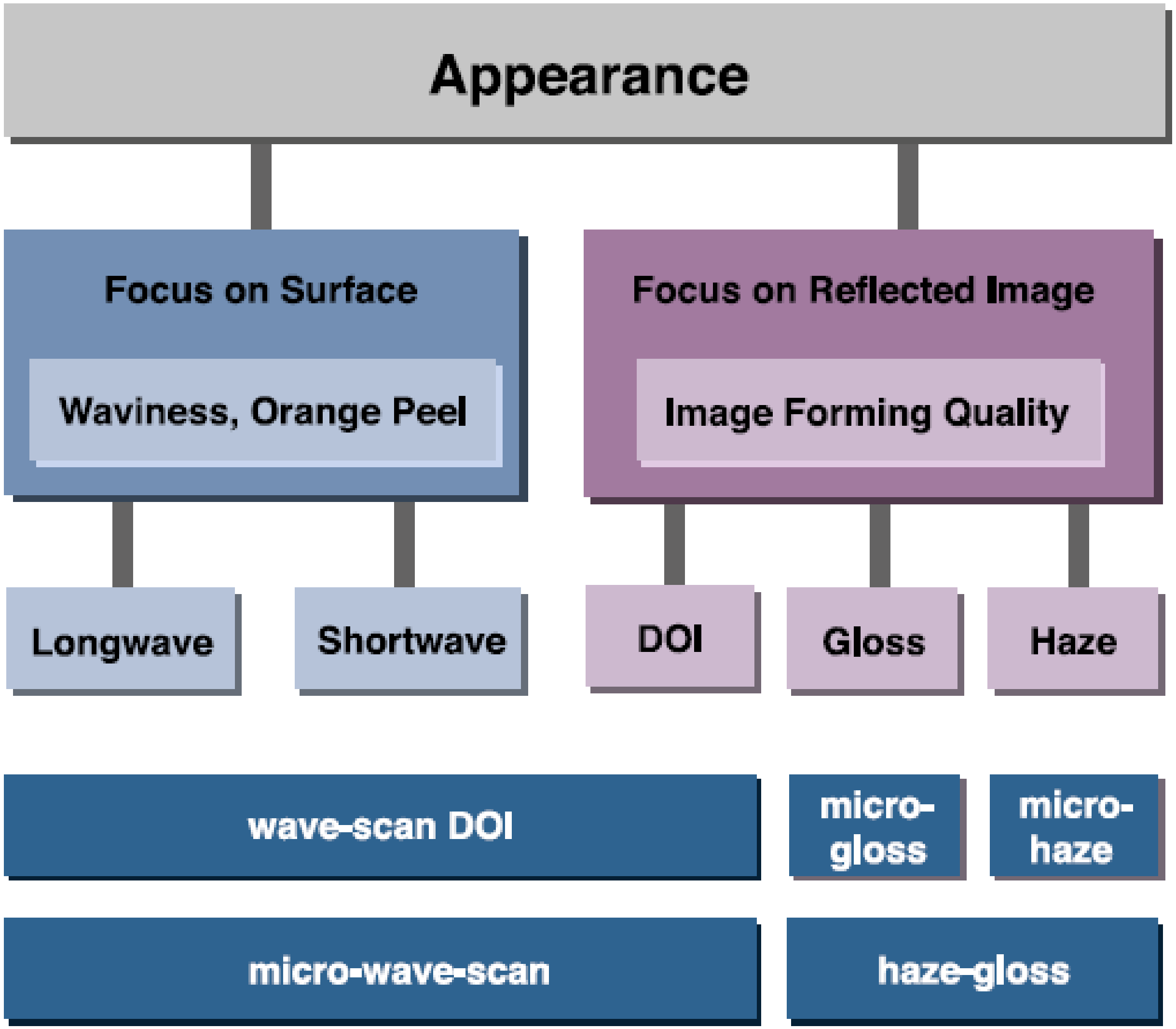
- **BYK-mac: graininess calculation**

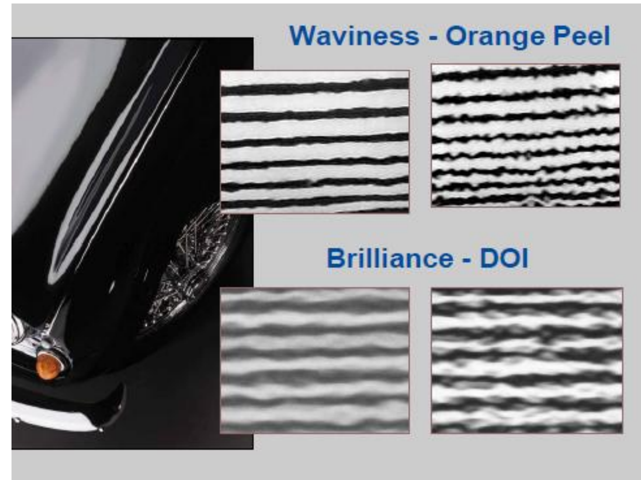
Analysis of Graininess Effect:

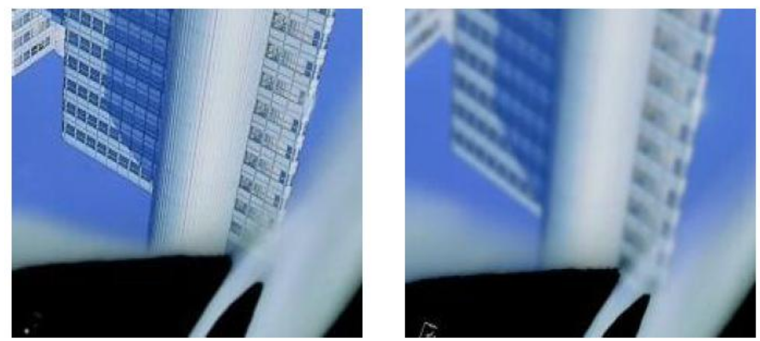
- Uniformity of light/dark areas is evaluated and summarized in a **Graininess** value
- 1-dimensional scale: relative dimension
- Solid color (very uniform) → Graininess = 0



Other visual appearance parameters







Good Poor

Contrast - Sharpness - Distinctness

Outline

- What is? How is it measured and perceived?
  - Current instrumentation and standards
- How these visual effects are caused by?
- New findings from the GVC-UA
- Future challenges:
  - Modeling and prediction of visual appearance
  - New materials and process technologies
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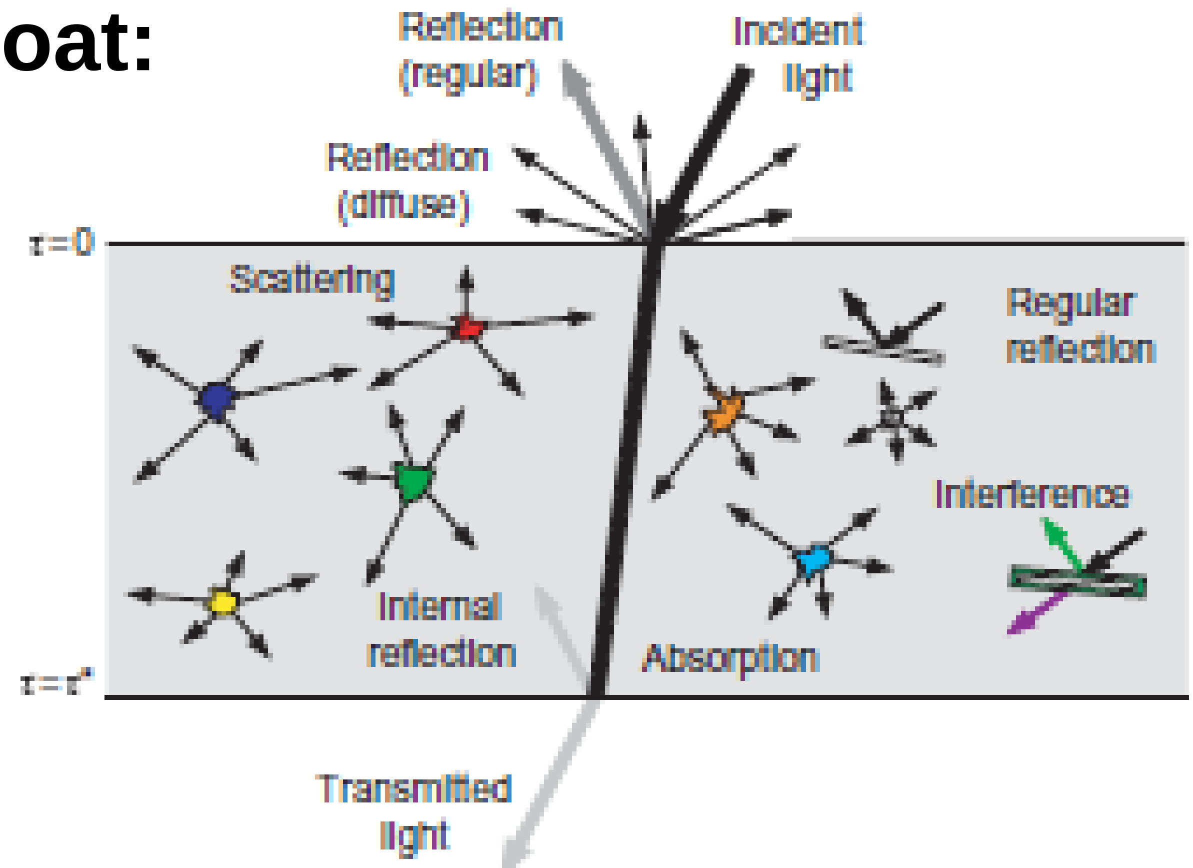
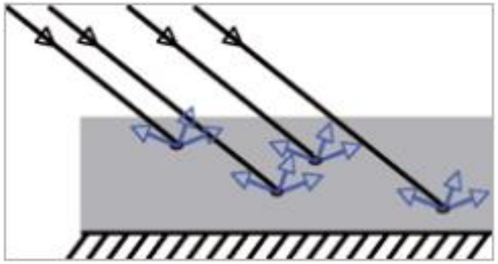
How visual effects are caused by?

- **Different types of pigments and arrangements inside the topcoat:**
  - Absorption
  - Scattering
  - Reflection
  - Interference
  - Transmission



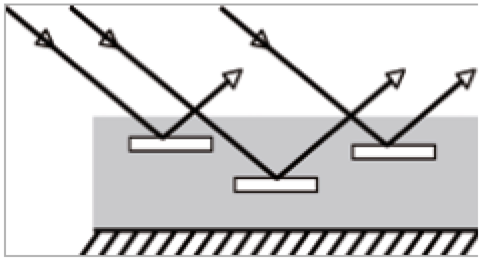
How visual effects are caused by?

- **Different types of pigments and arrangements inside the topcoat:**



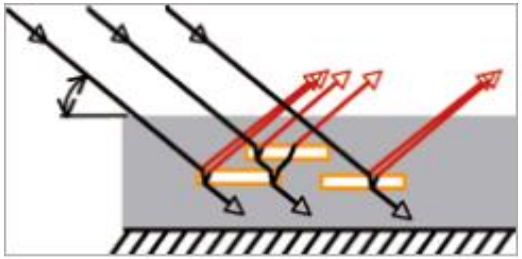
Absorption pigments

- **Color pigments (solid shades)**
  Light absorption and reflection in all directions (scattering)



Metallic pigments

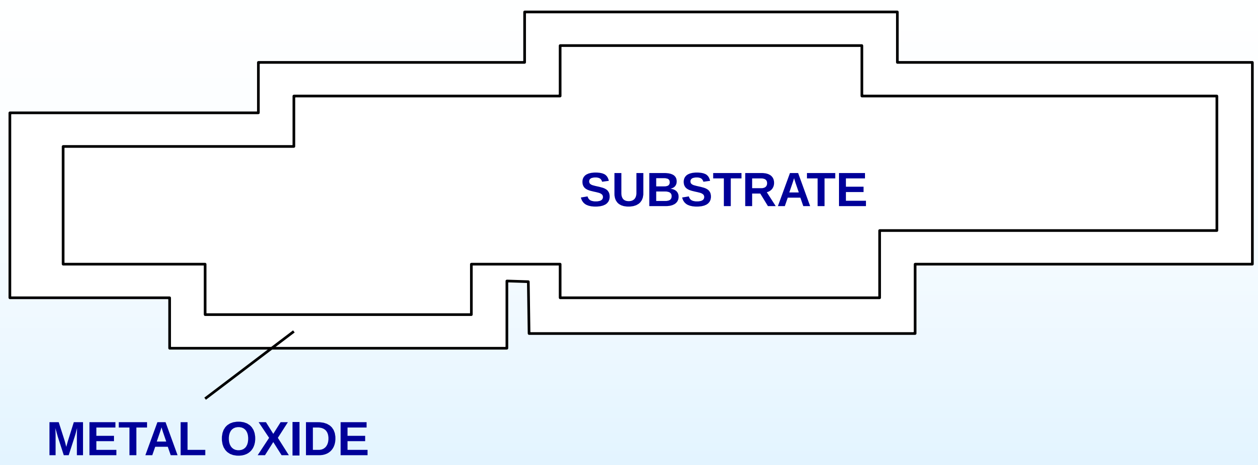
- **Aluminium pigments**
  Light mirroring and adjusted reflection
- **Interference pigments**
  Light refraction and selective reflection



Interference pigments

How visual effects are caused by?

- **Shapes and sizes of special-effect pigments:**

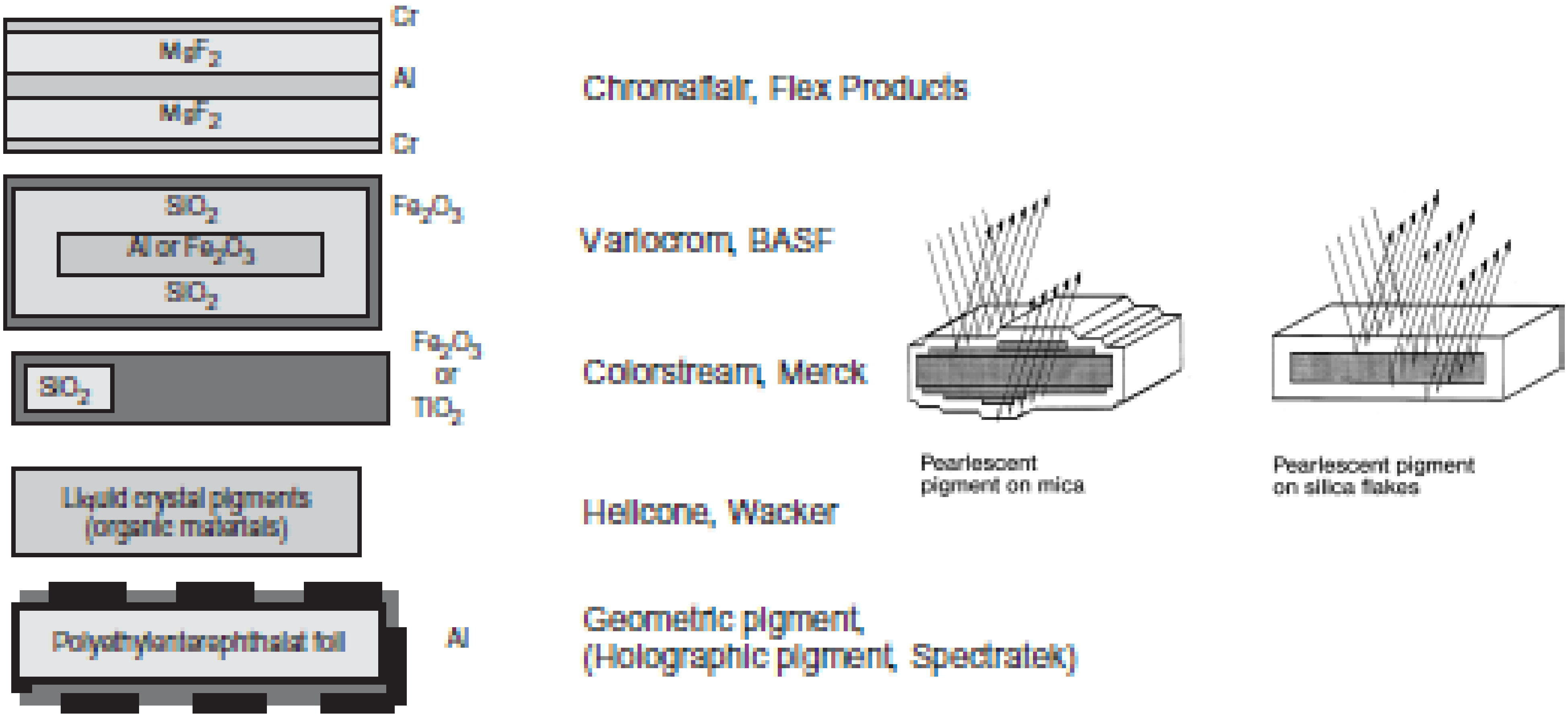


SUBSTRATE
Mica
Silicium Oxide (synthetic)
Aluminium
Aluminium Oxide (synthetic)
plated Iron Oxide (synthetic)

METAL OXIDE
TiO_2 (Rutil)
$FeTiO_3$
$CoTiO_3$
Fe_2O_3
Cr_2O_3
multiple layer

How visual effects are caused by?

- **Shapes and sizes of special-effect pigments:**



How visual effects are caused by?

- **Shapes and sizes of special-effect pigments:**
- ***Iriodin/Afflair Merck:***

natural mica coated with high refractive metal oxide like TiO_2 or Fe_2O_3

- ***Xirallic Merck:***

Al_2O_3-platelets coated with high refractive metal oxide

- ***Colorstream Merck:***

SiO_2-platelets coated with high refractive metal oxide

- ***Pyrisma Merck:***

special mica coated with high refractive metal oxide

How visual effects are caused by?

- **Shapes and sizes of special-effect pigments:**
- ***Variocrom BASF:***

Optical Variable Pigments (OVP) chemical vapor deposition

- ***ChromaFlair Flex Products:***

5-layers with opaque reflector, dielectrical and semi-transparent layers

- ***SpectraFlair Flex Products:***

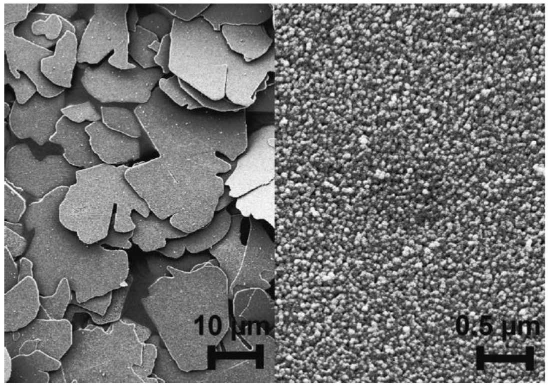
microstructure surface and opaque reflector layer

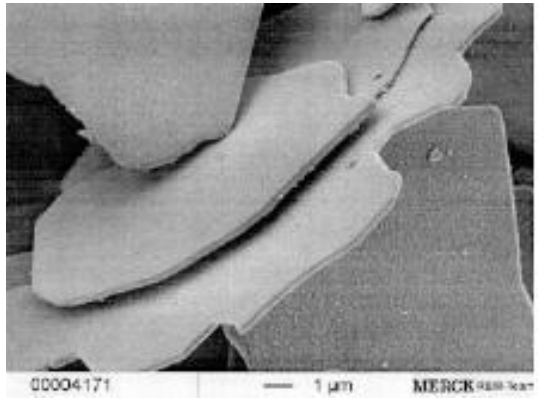
- ***Helicone Wacker Chemie:***

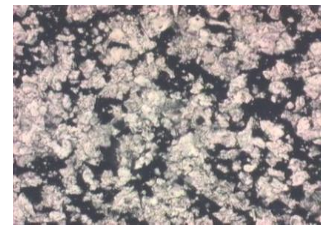
Liquid Crystals Polymers (LCP)

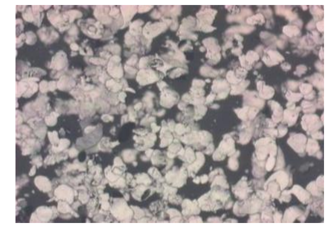
How visual effects are caused by?

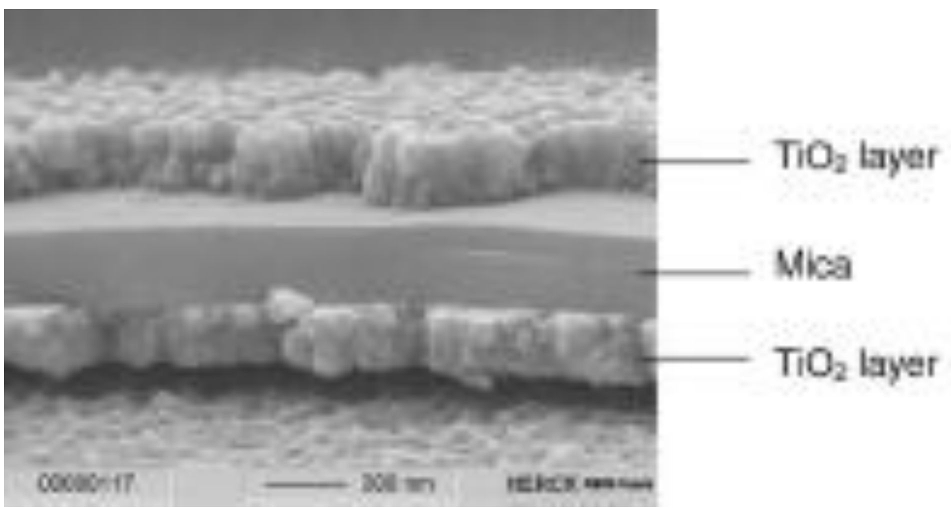
- **Shapes and sizes of special-effect pigments:**

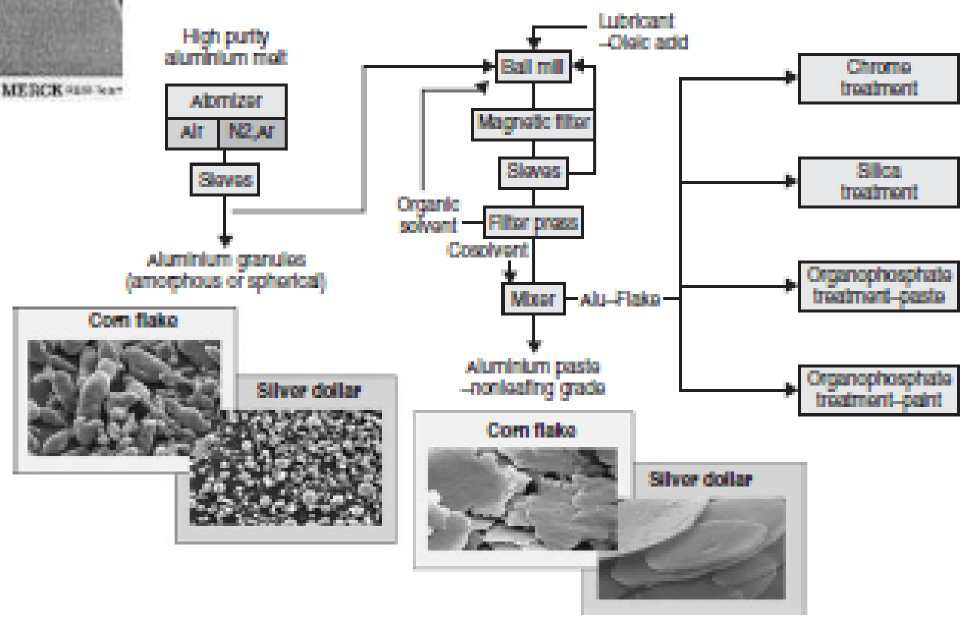






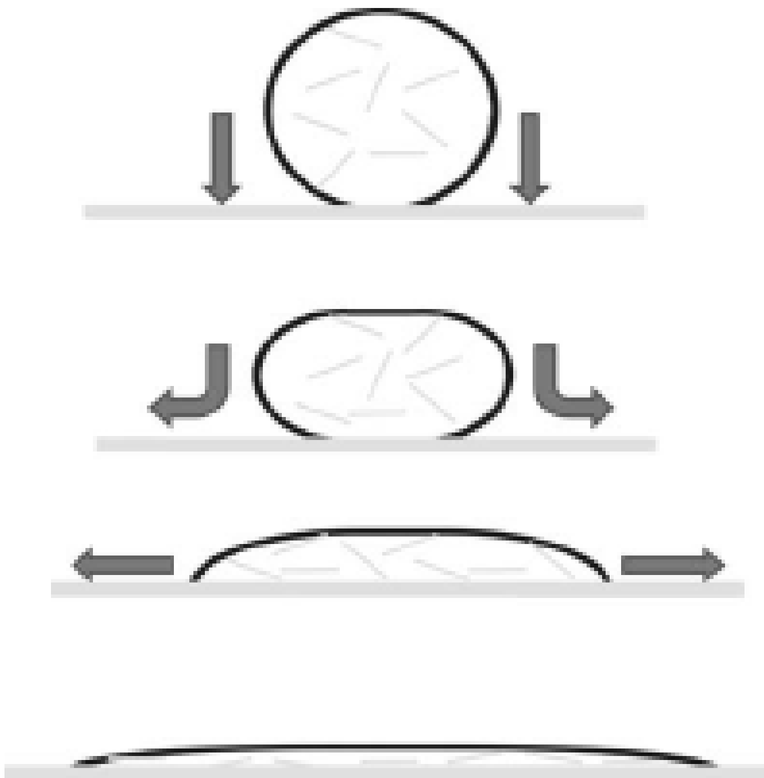


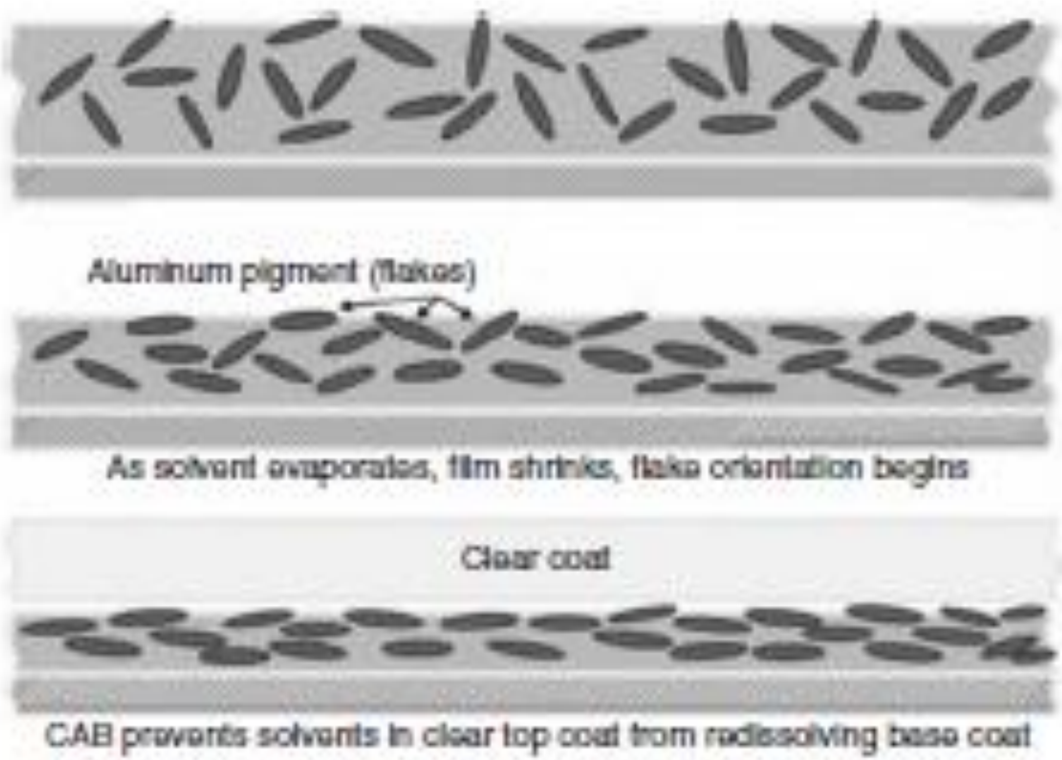




How visual effects are caused by?

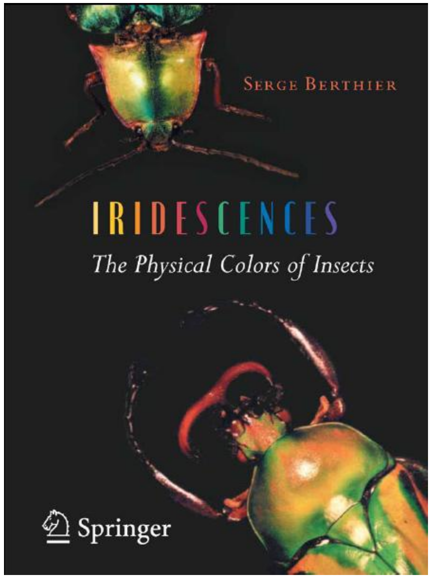
- Flake orientation during film formation and by film shrinkage:

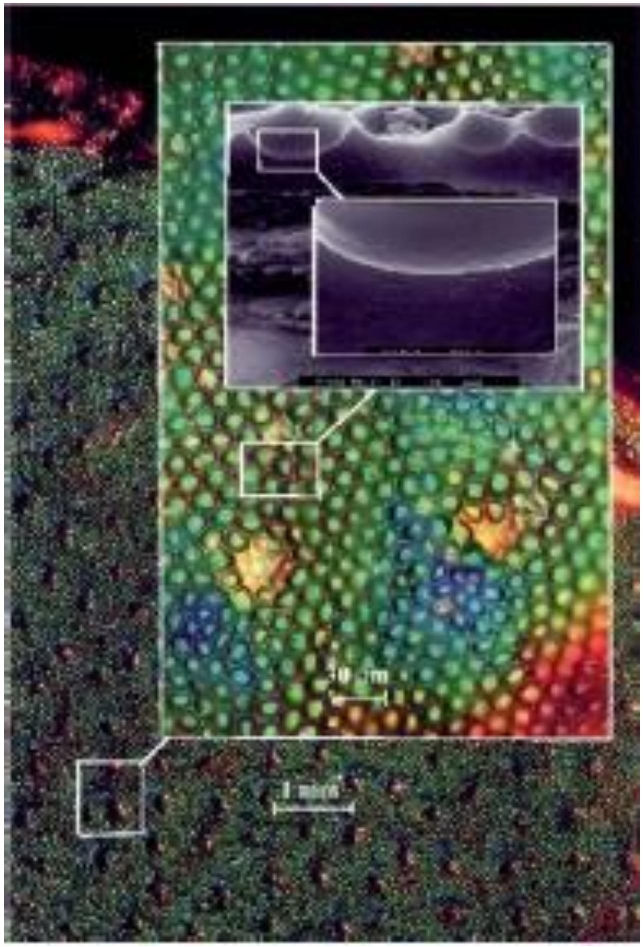




Are there these visual effects in Nature?

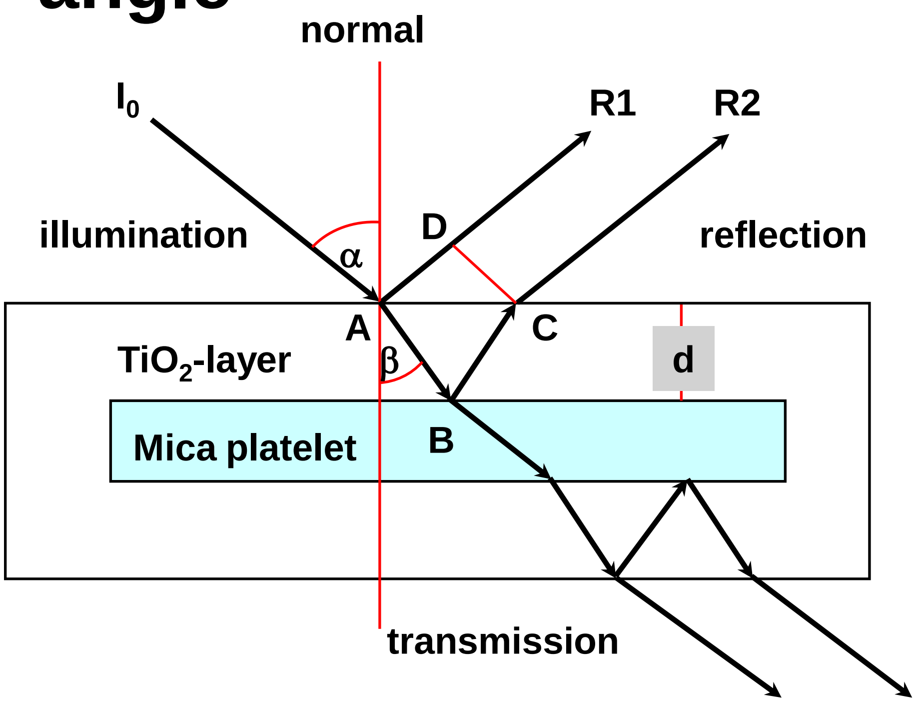
- http://www.webexhibits.org/causesofcolor/15A.html
  - 1-D structure : interference
  - 2-D structure: interferences and diffraction
  - 3-D structure: crystalline diffraction
  - Amorphous structures: scattering





Optics of special-effect pigments

- **Resulting color depends on:**
  - **Thickness of external layer, n, and, illumination angle**



$$\delta = n(AB + BC) - AD$$

$$\delta = 2d\sqrt{n^2 - \sin^2\alpha}$$

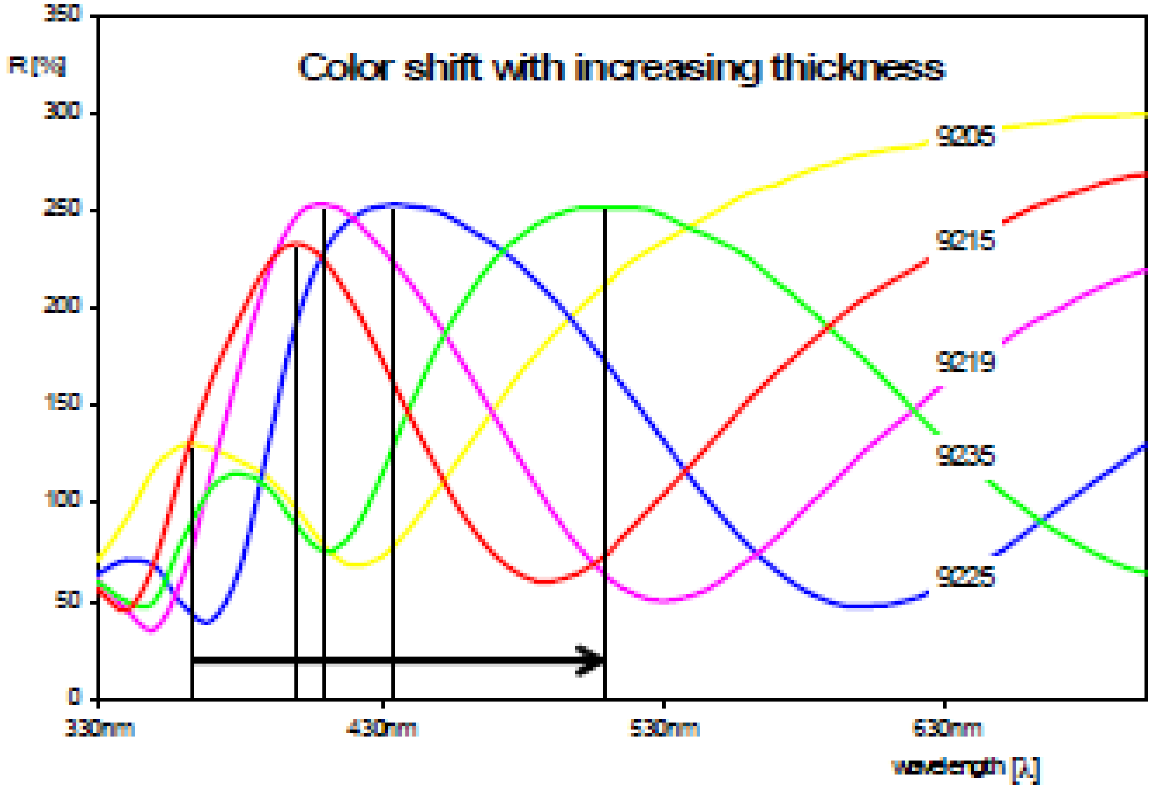
$$\Delta = 2d\sqrt{n^2 - \sin^2\alpha} + \frac{\lambda}{2}$$

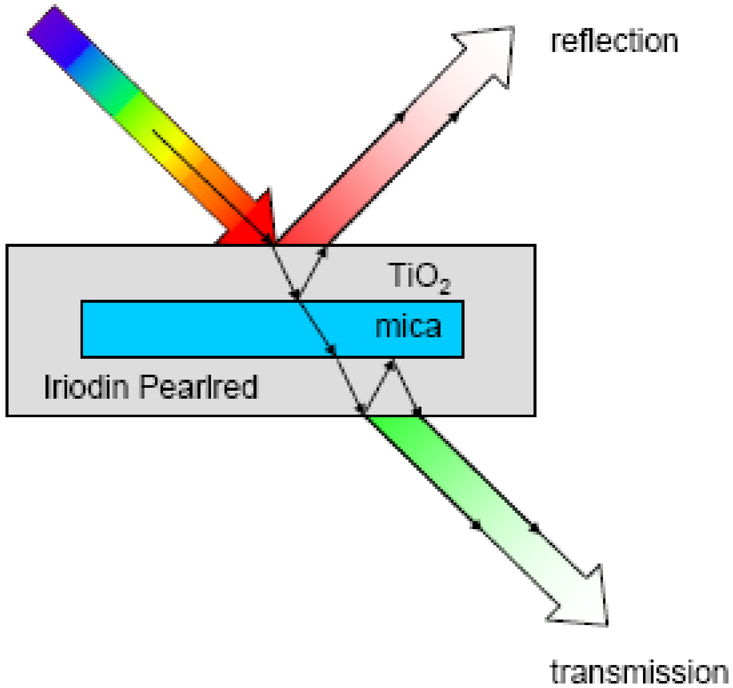
$$\lambda_{max} = \frac{4d}{2m+1}\sqrt{n^2 - \sin^2\alpha}\,,$$

$$\textit{with} \quad m = 0, 1, 2, 3, \ldots$$

Optics of special-effect pigments

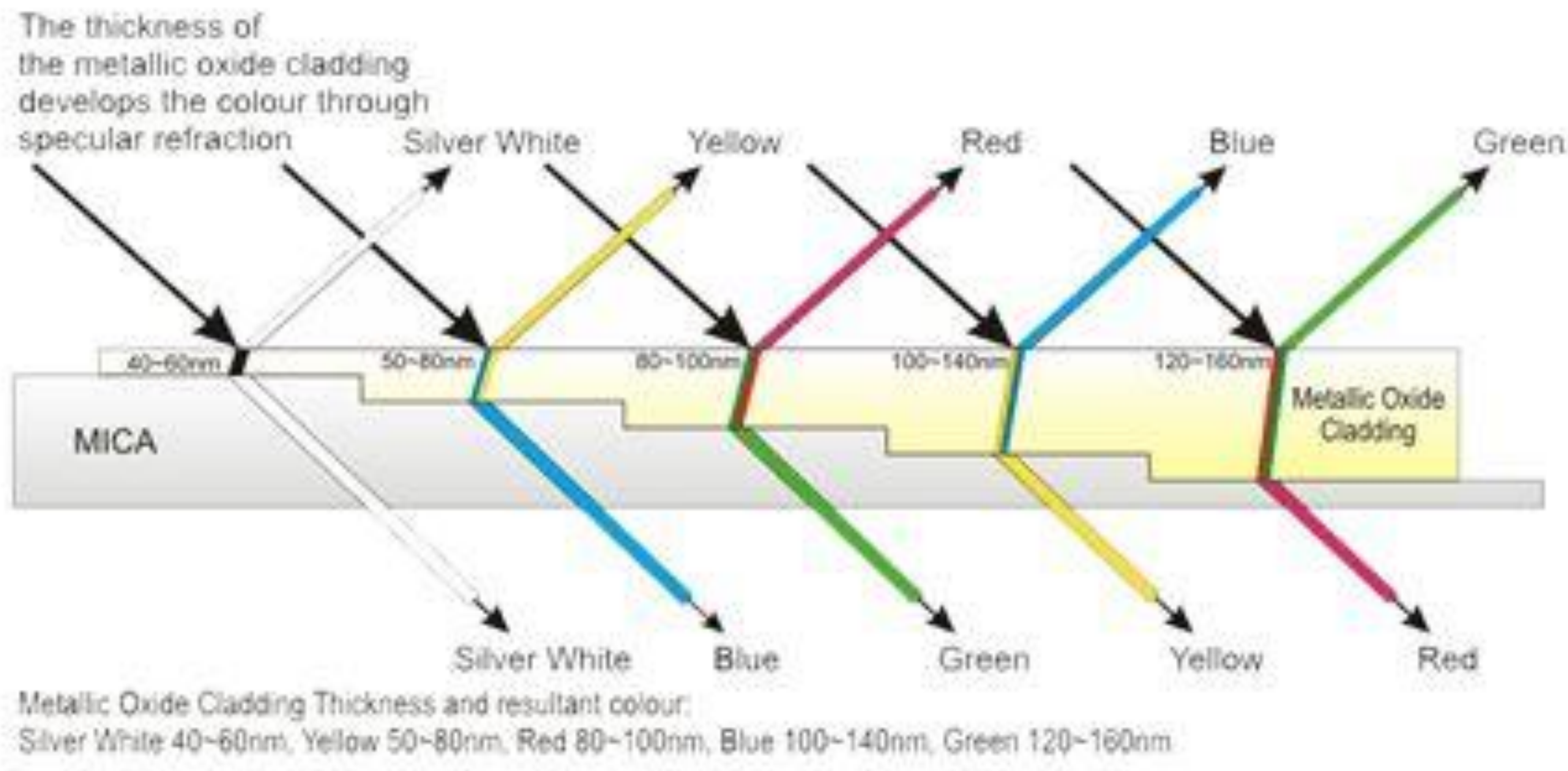
- **Impact of thickness:**





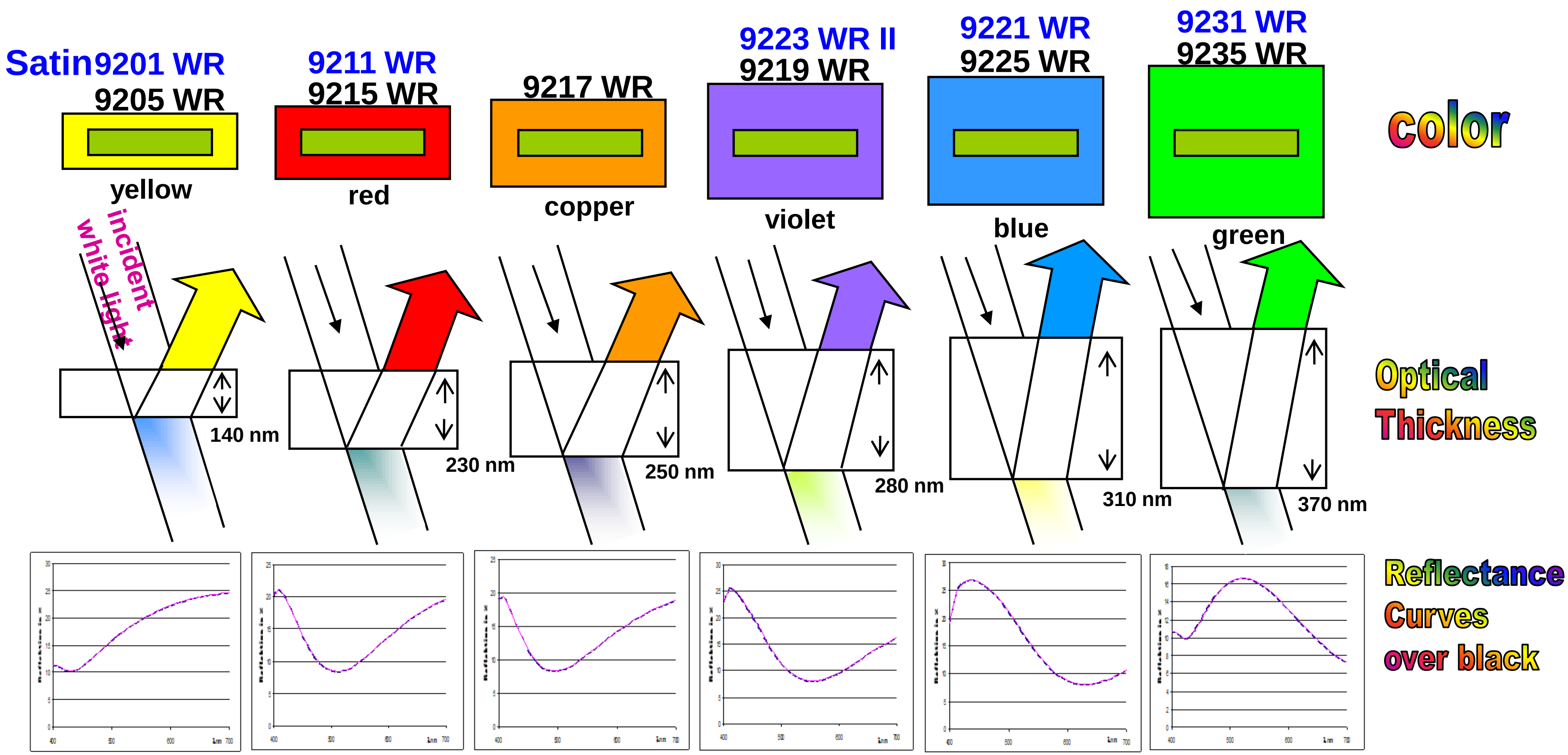
Optics of special-effect pigments

- **Impact of thickness:**



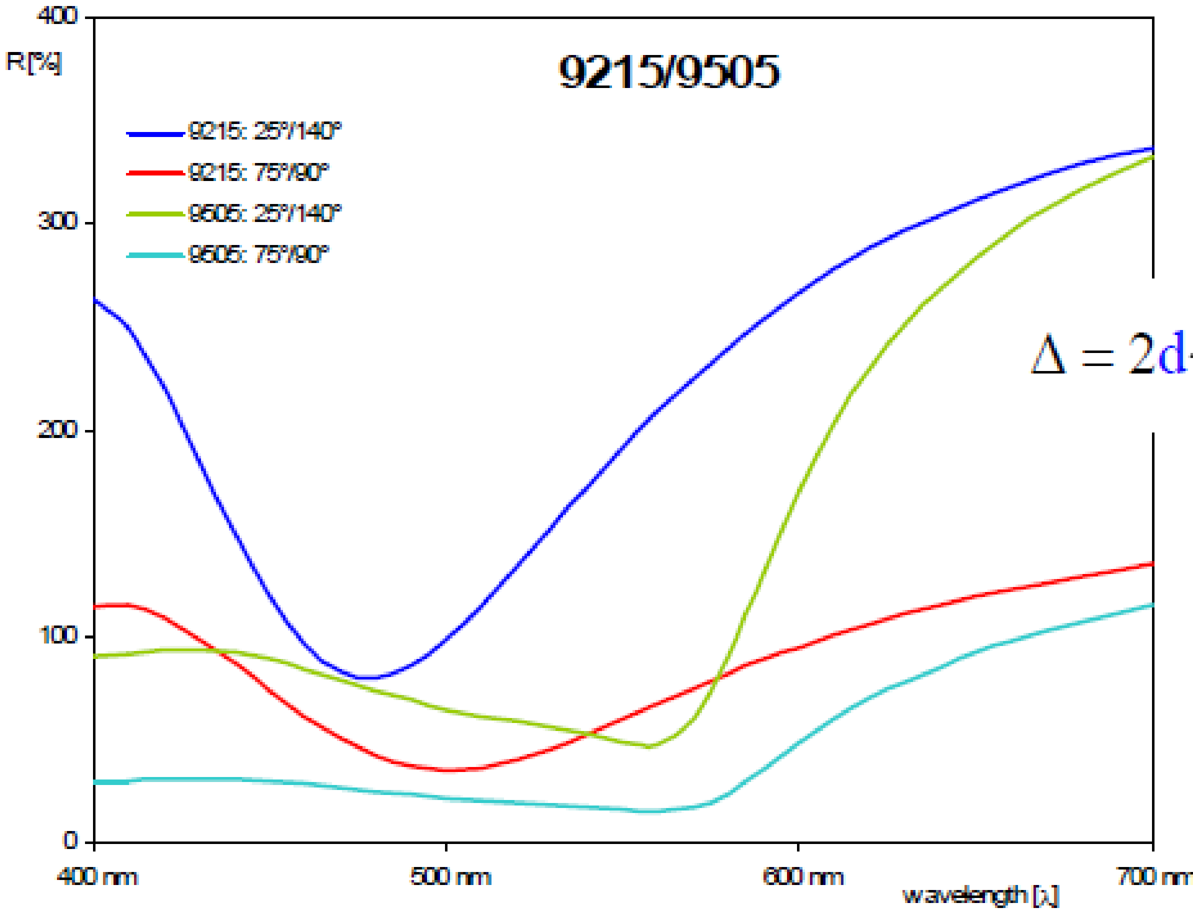
Optics of special-effect pigments

- **Impact of thickness:**



Optics of special-effect pigments

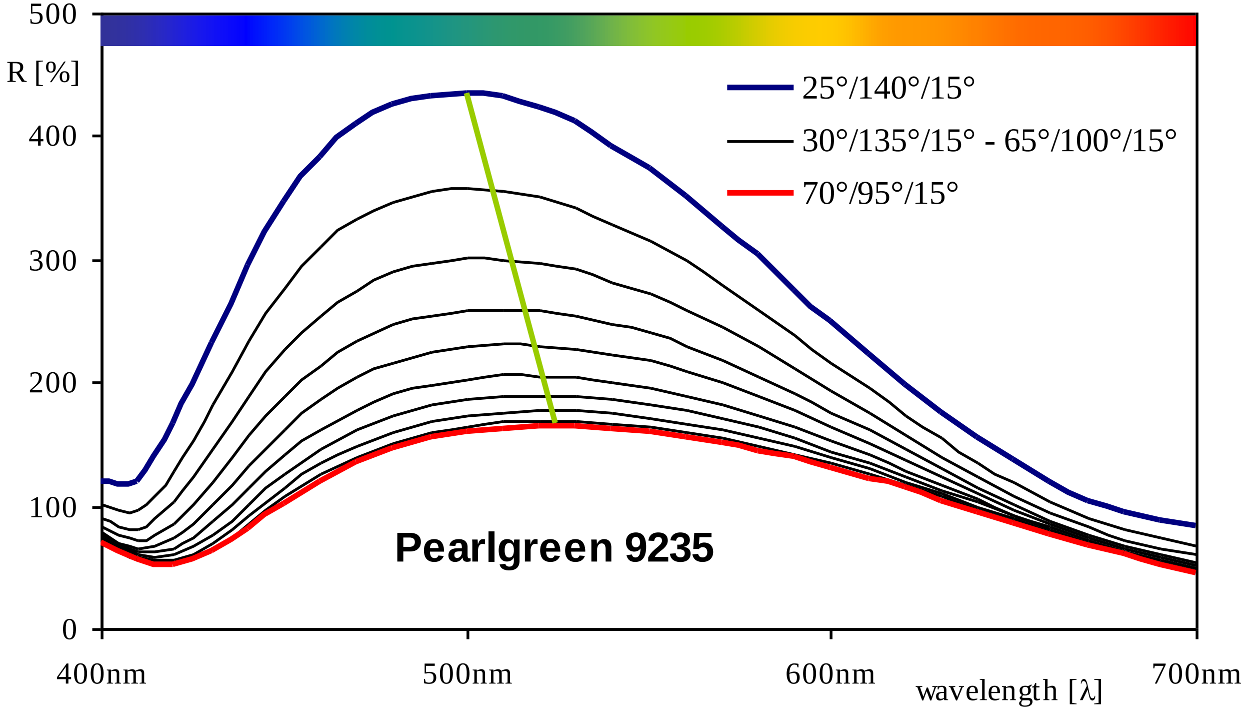
- **Impact of refractive index:**

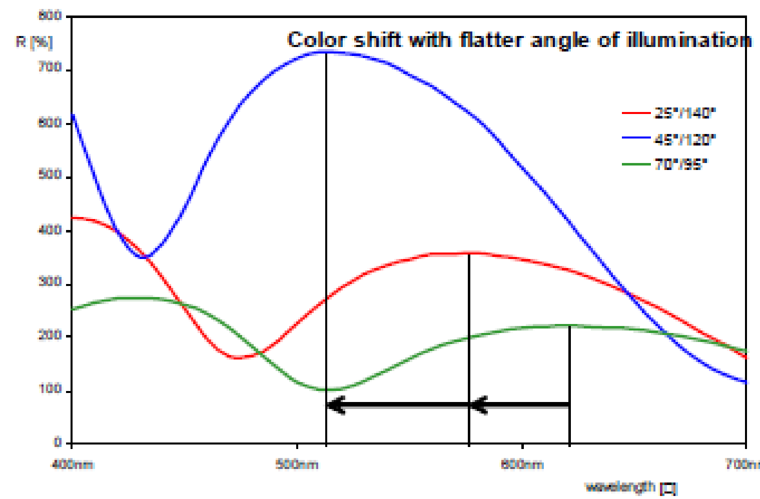


$$\Delta = 2d\sqrt{n^2 - \sin^2\alpha} + \frac{\lambda}{2}$$

Optics of special-effect pigments

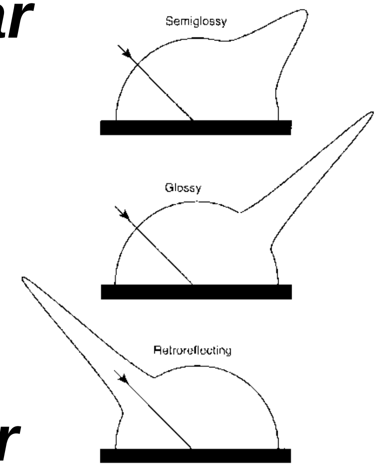
- **Impact of illumination angle:**

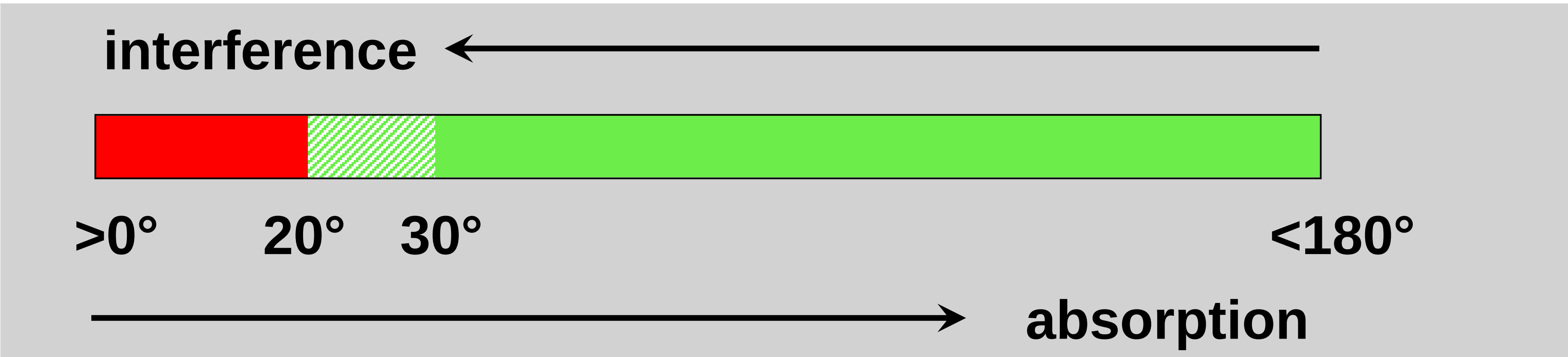




Color system with 3 components

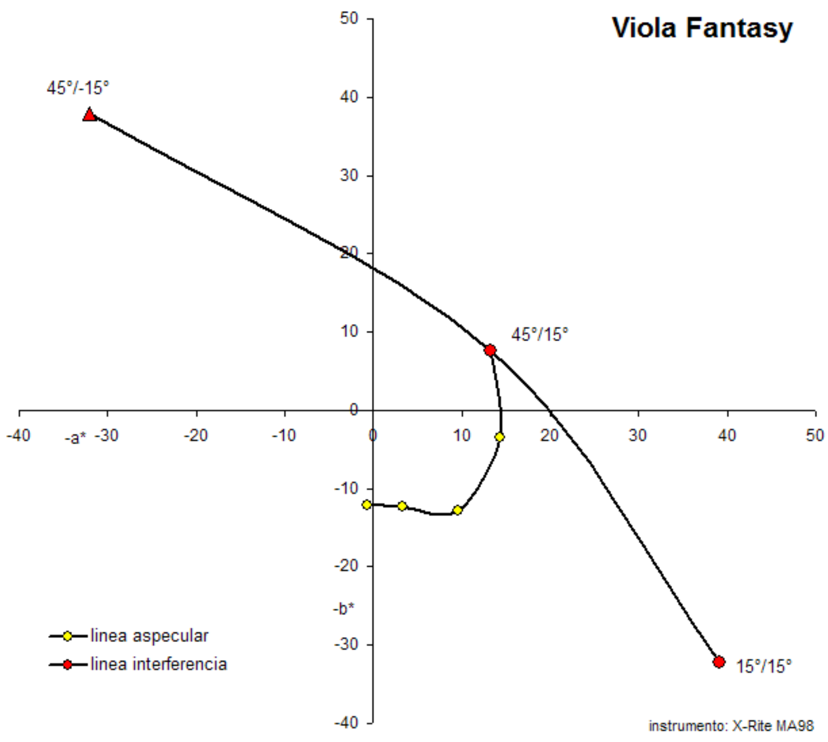
- **Interference component**
  main influence on color system up to 20° aspecular
- **Transition zone**
  variably influence between 20° and 30° aspecular
- **Absorbing component**
  main influence on color system from 30° aspecular

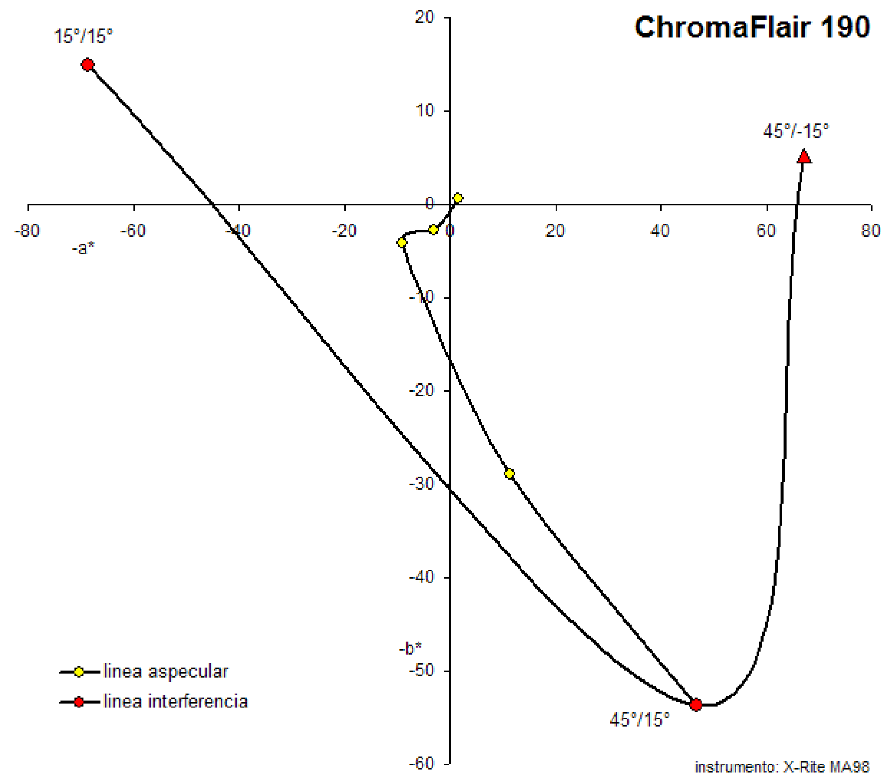




Identification of special-effect pigments

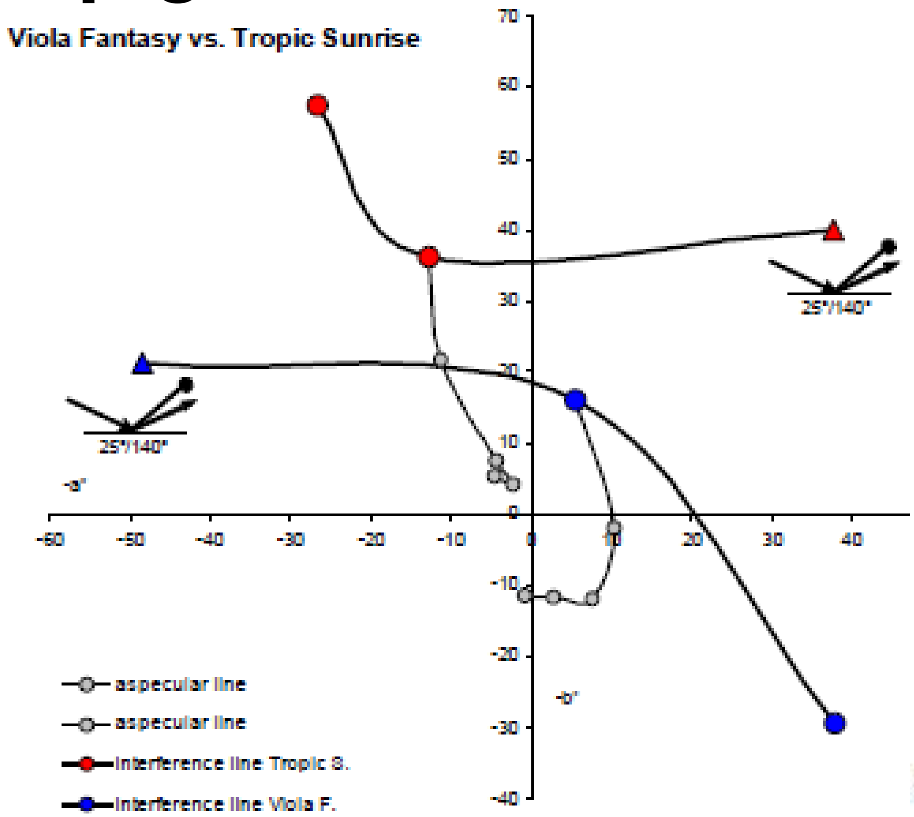
- **T-shape for interference pigments:**
  - **Aspecular vs. Interference lines: both necessary**

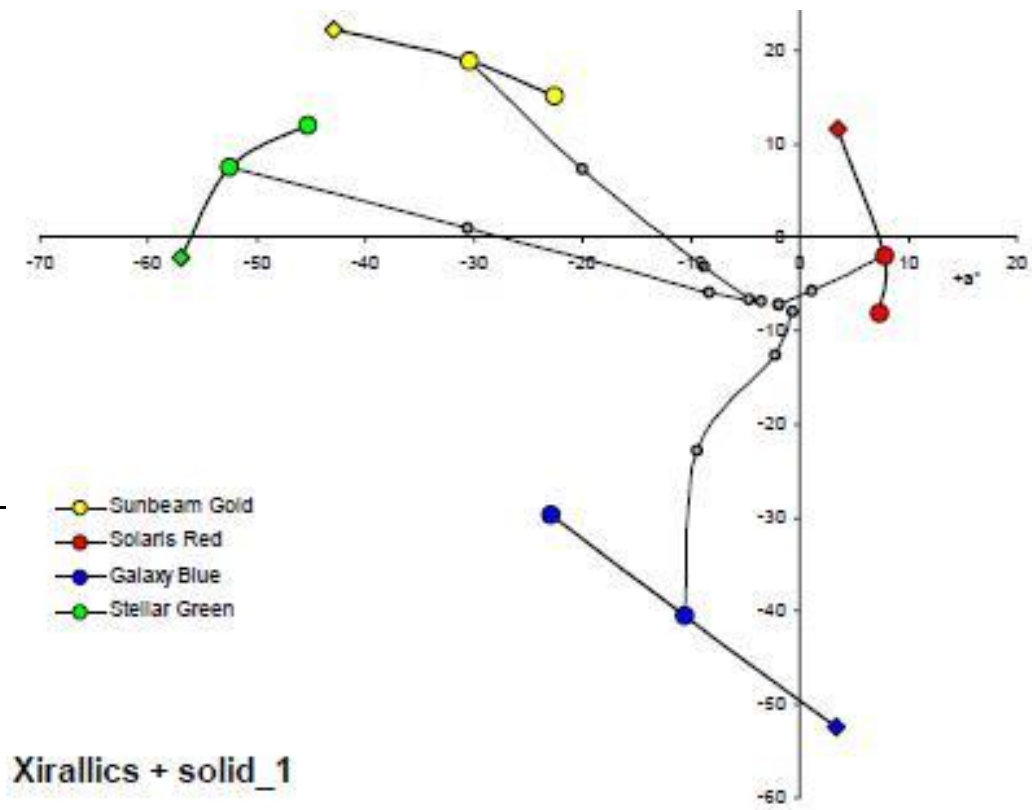




Identification of special-effect pigments

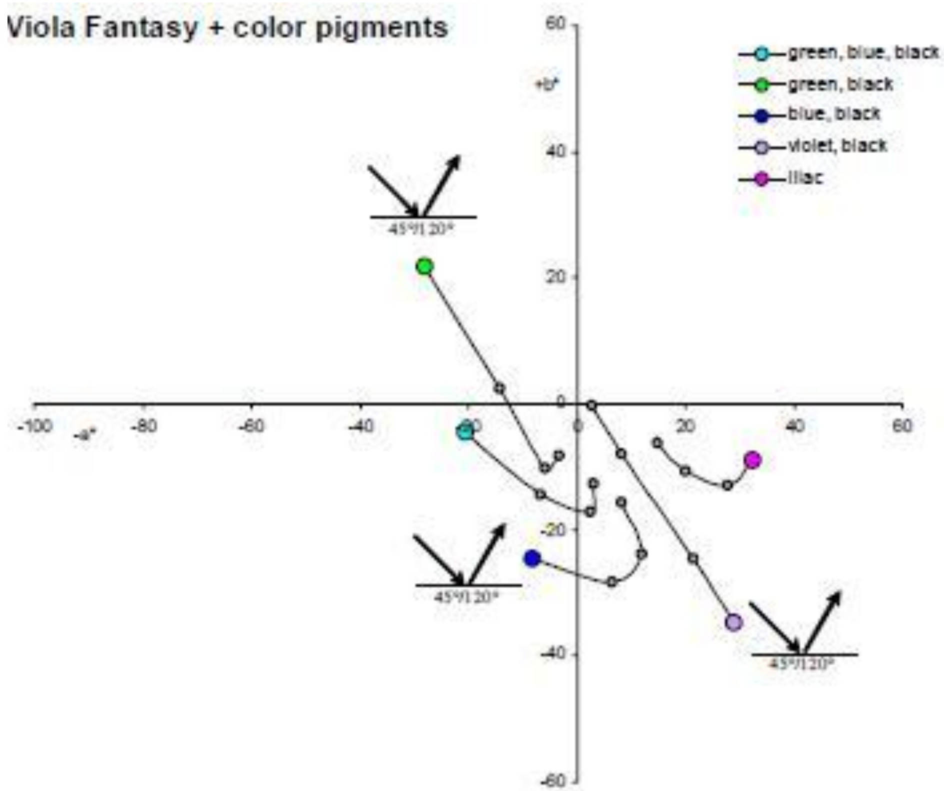
- **Mixing special-effect pigments with absorbing pigments:**

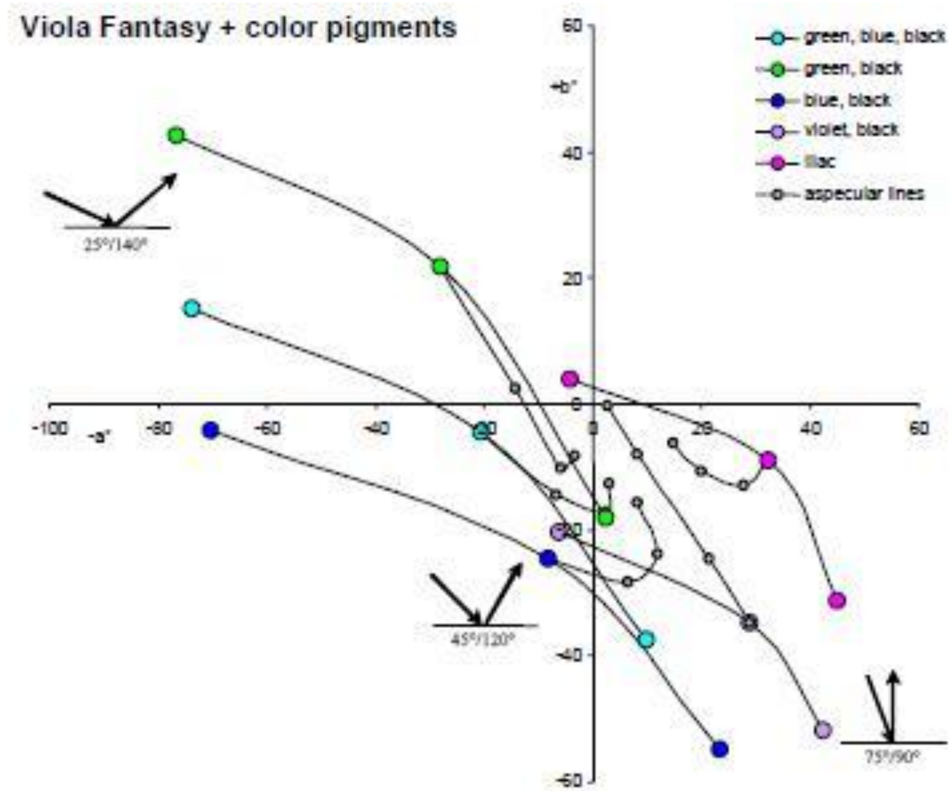




Identification of special-effect pigments

- **Mixing special-effect pigments with absorbing pigments:**





Outline

- What is? How is it measured and perceived?
  - Current instrumentation and standards
- How these visual effects are caused by?
- New findings from the GVC-UA
- Future challenges:
  - Modeling and prediction of visual appearance
  - New materials and process technologies
  - Visual appearance matching control management

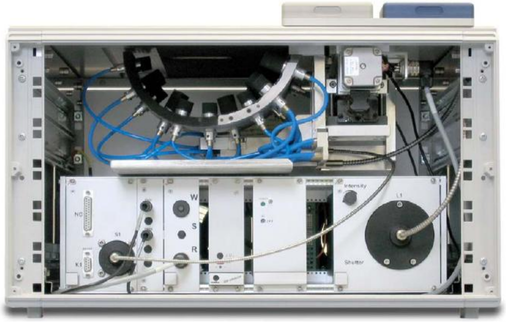
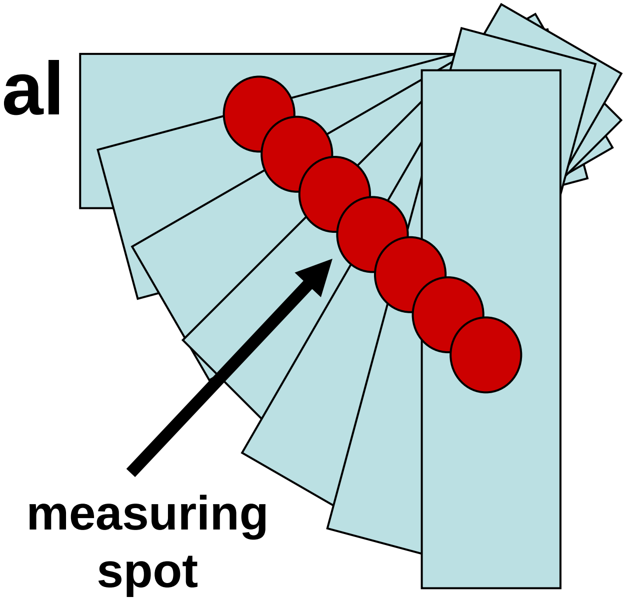
New findings from the GVC-UA

- Optical anisotropy in special-effect pigments
  - Published in Journal of Modern Optics (2009)
- Color gamuts outside Rösch-MacAdam limits
  - Accepted in Applied Optics (2011)
- Reproducibility between multi-gonios
  - Sent to Color Research & Application (2012)

Optical anisotropy in flake pigments

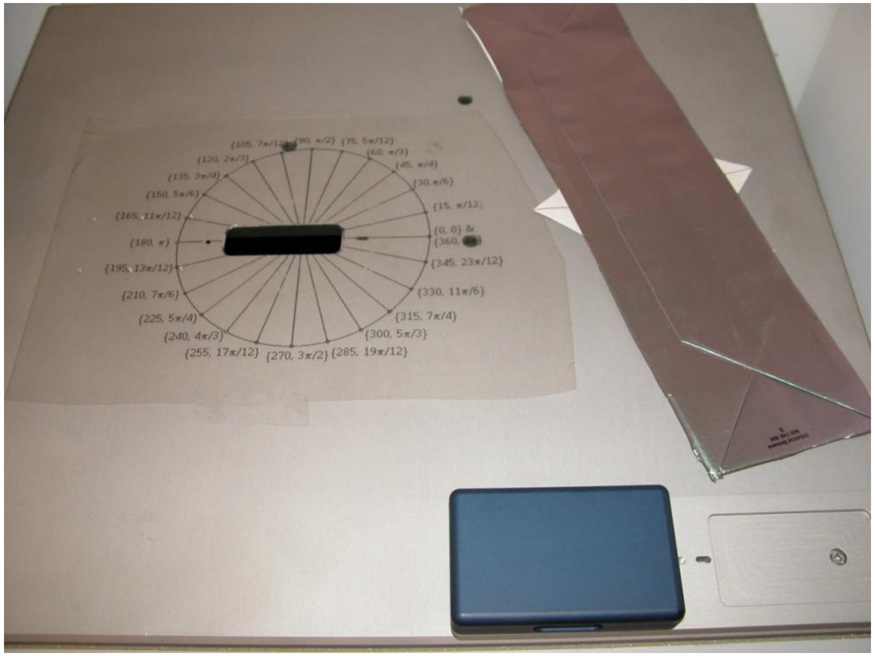
- Purpose:
  - To obtain more information about the sBDRF of gonio-apparent samples with current instruments
- Our proposal
  - Rotating sample around the normal
  - Multi-gonio-spectrophotometer

with 10 angle-pairs

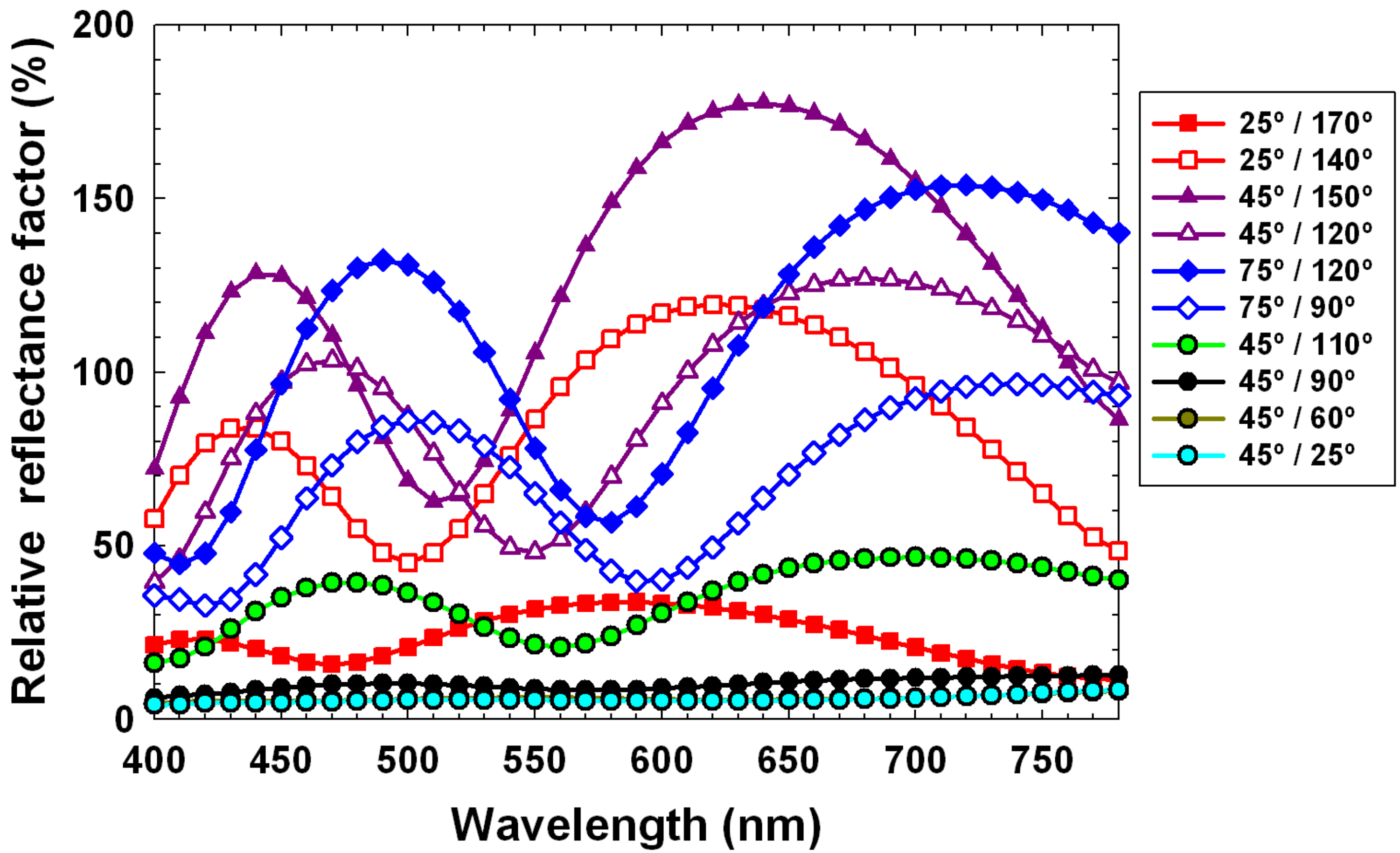
Optical anisotropy in flake pigments

- **Material and methods:**
- **One gonio-apparent sample:**
  - Merck product: Colorstream T20-02 Arctic Fire Exterior (T20-02) PSD 5-40 μm Rutile
  - Big size
    - Aperture size: 22 x 69 mm
    - Average measuring area:
      - 17,6 x 32,2 mm
- **One gonio-template**
  - Rotating angle step:
    - 15 deg, from 0 to 360 deg



Optical anisotropy in flake pigments

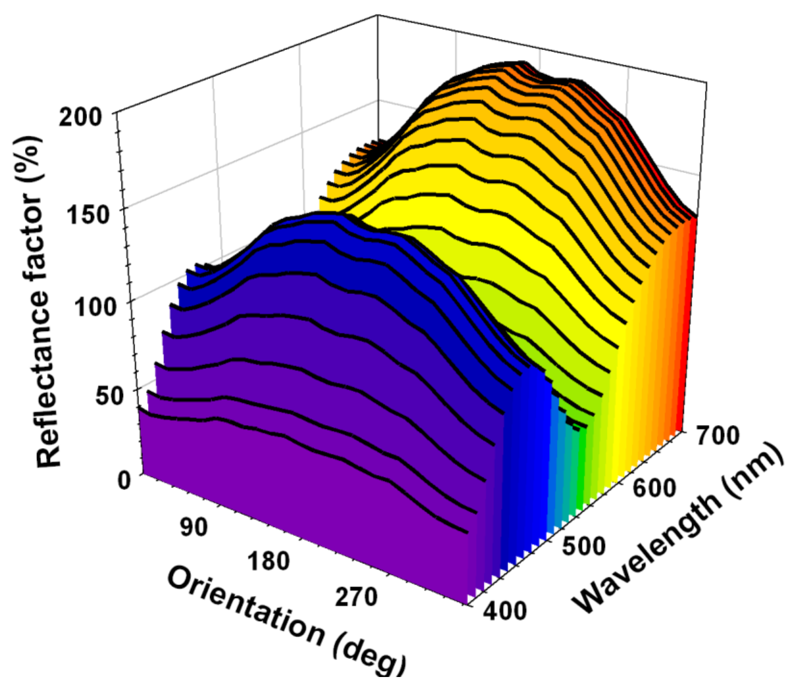
- Results (I): Orientation 0 deg



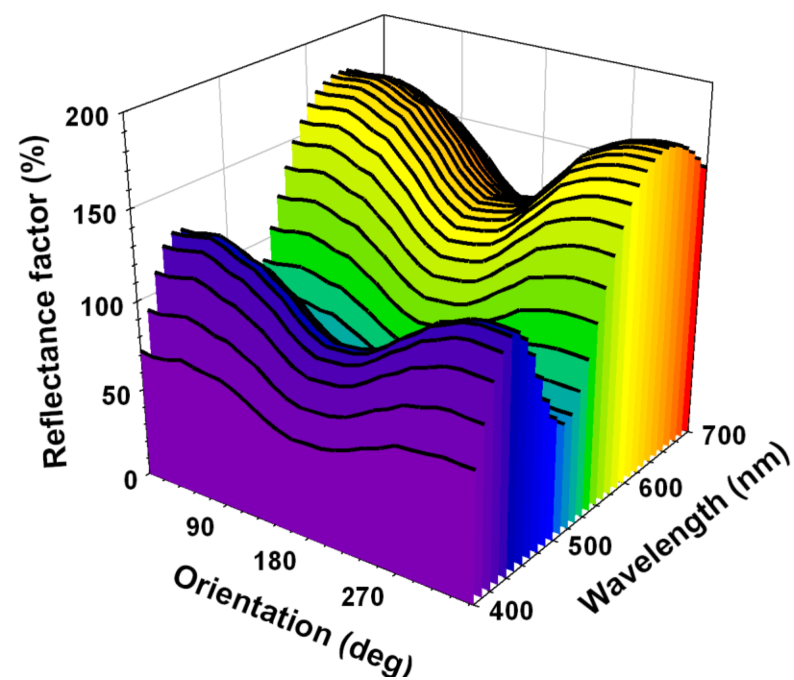
Optical anisotropy in flake pigments

- Results (II): 3D spectral data
- Geometries 45/120 vs. 45/150 deg
  - Shift to the peaks towards longer wavelengths from “trans” to “cis”

Geometry: 45/120



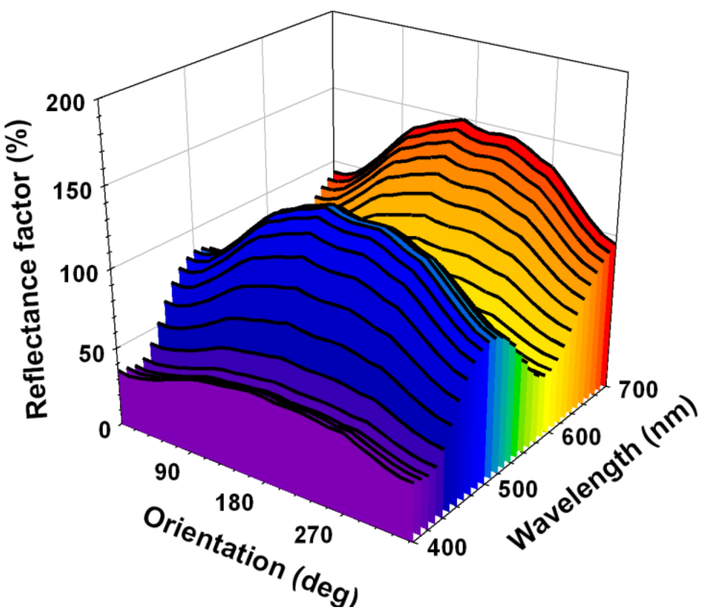
Geometry: 45/150



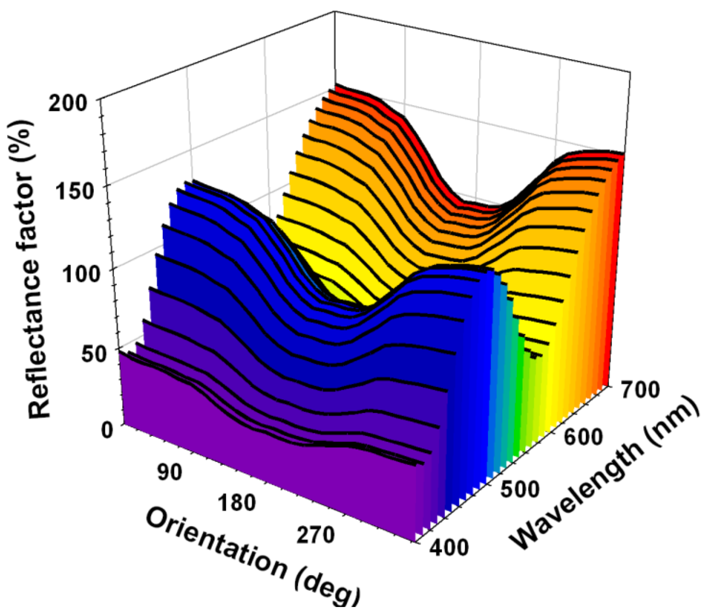
Optical anisotropy in flake pigments

- **Results (III): 3D spectral data**
- **Geometries 75/90 vs. 75/120 deg**
  - **There is not spectral reversibility between orientation pairs like 0-180, 15-195 deg, …, etc**

Geometry: 75/90

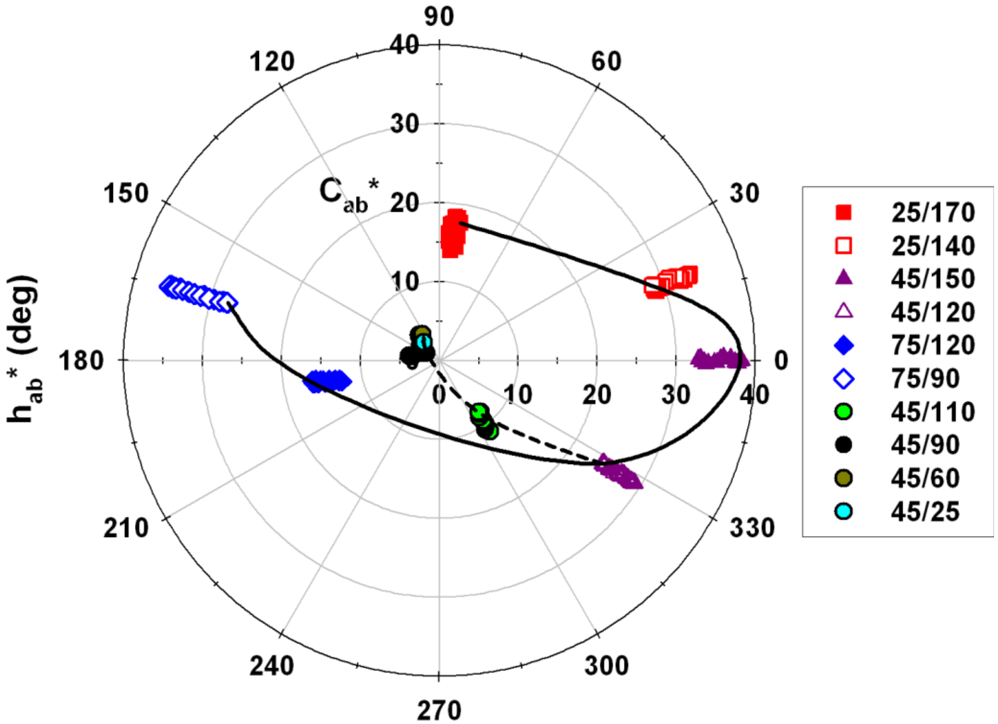


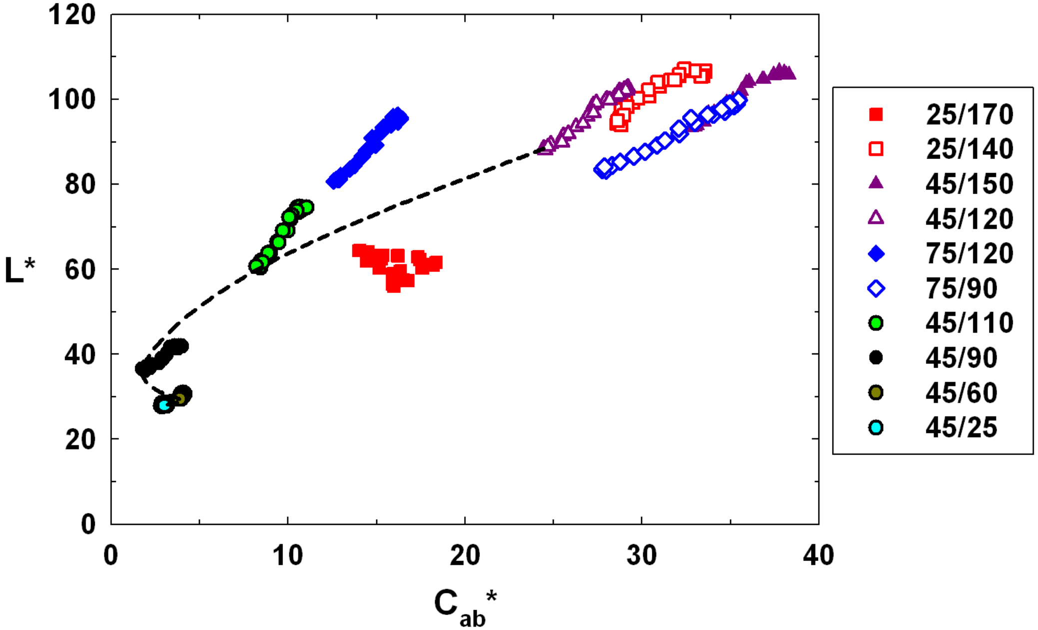
Geometry: 75/120



Optical anisotropy in flake pigments

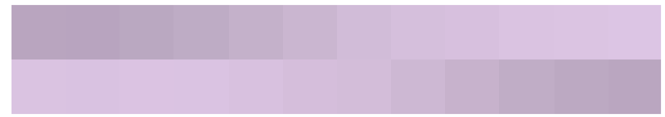
- Results (IV): all orientations & geometries

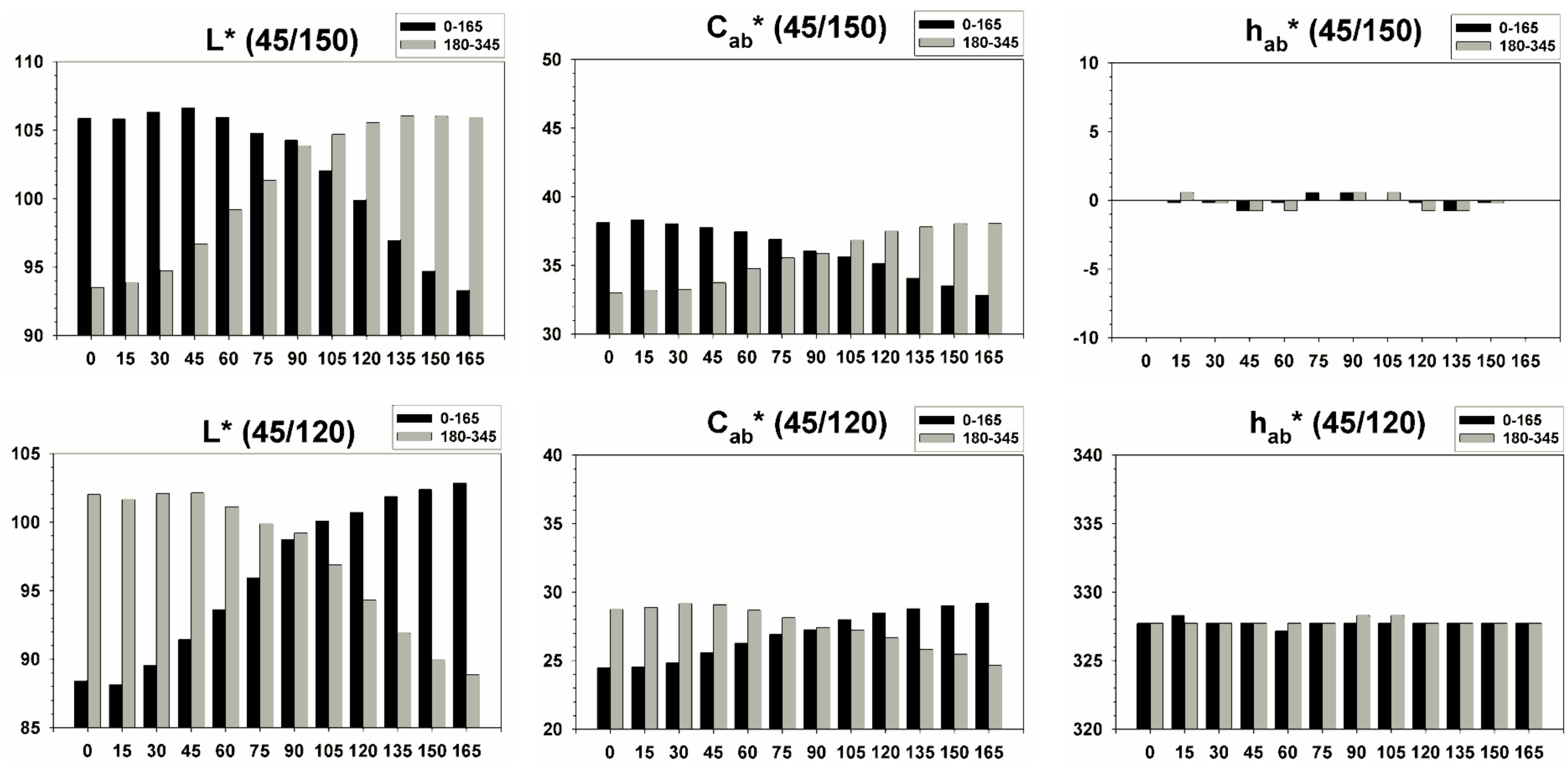




Optical anisotropy in flake pigments

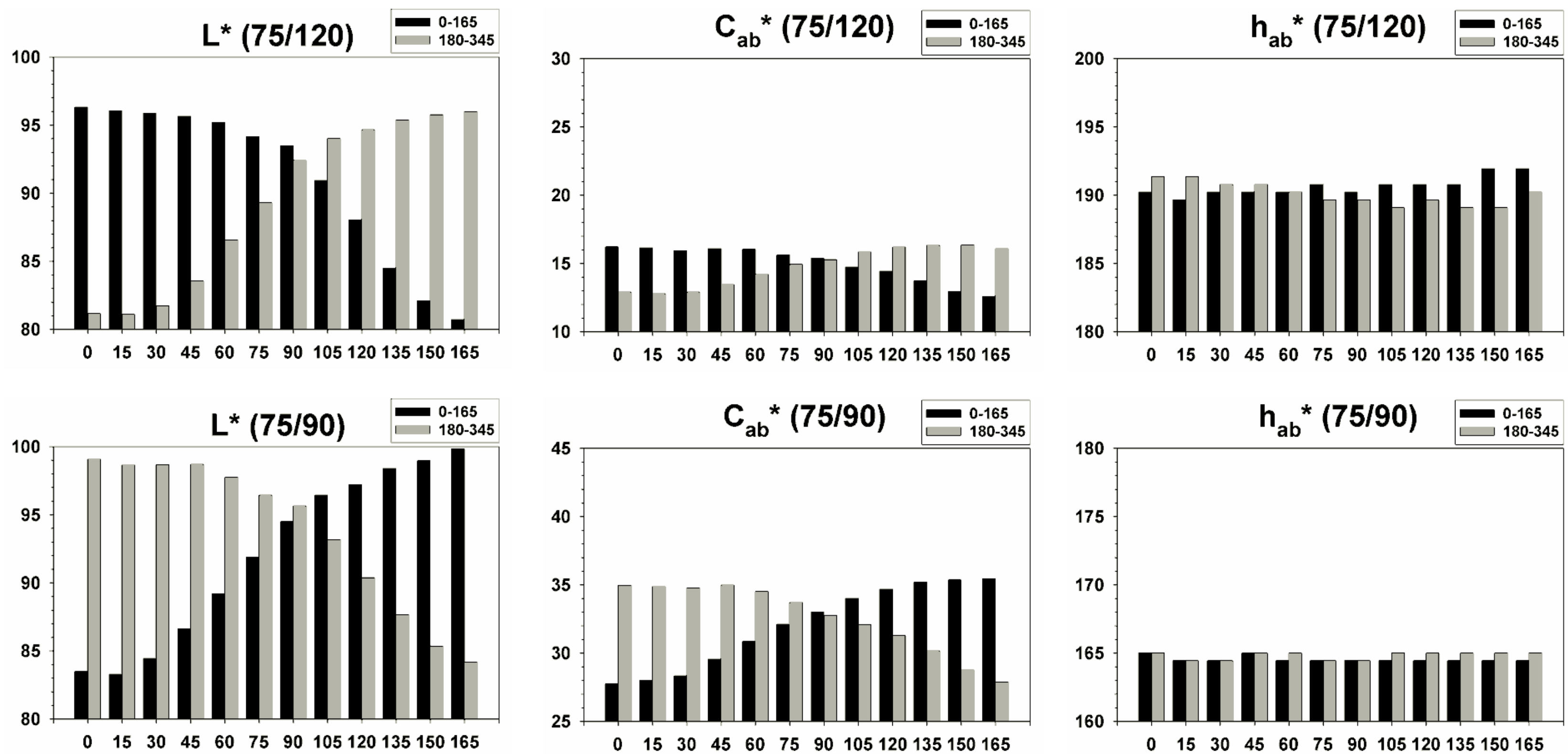
- **Results (V): analysis of chromatic reversibility**





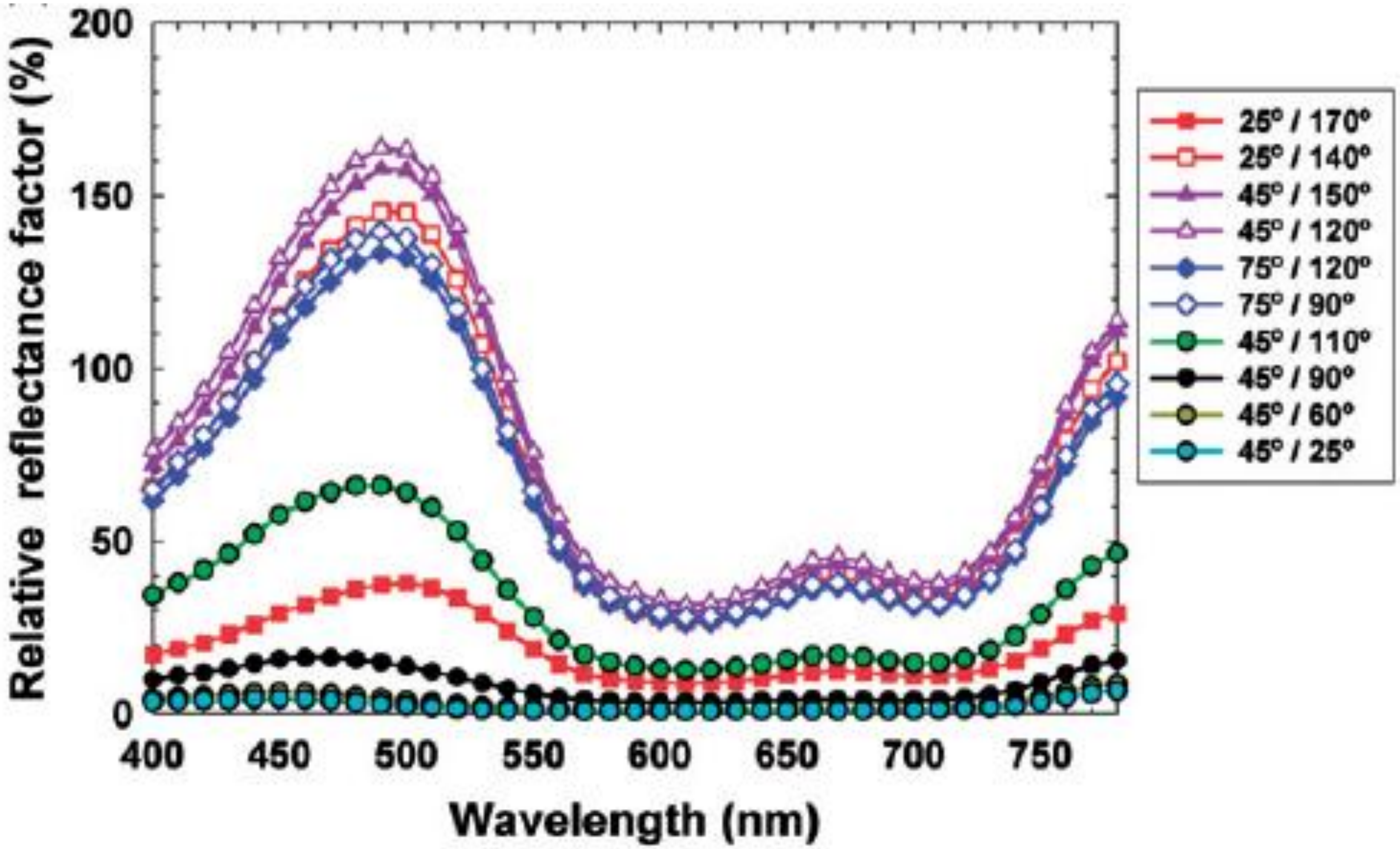
Optical anisotropy in flake pigments

- **Results (VI): analysis of chromatic reversibility**



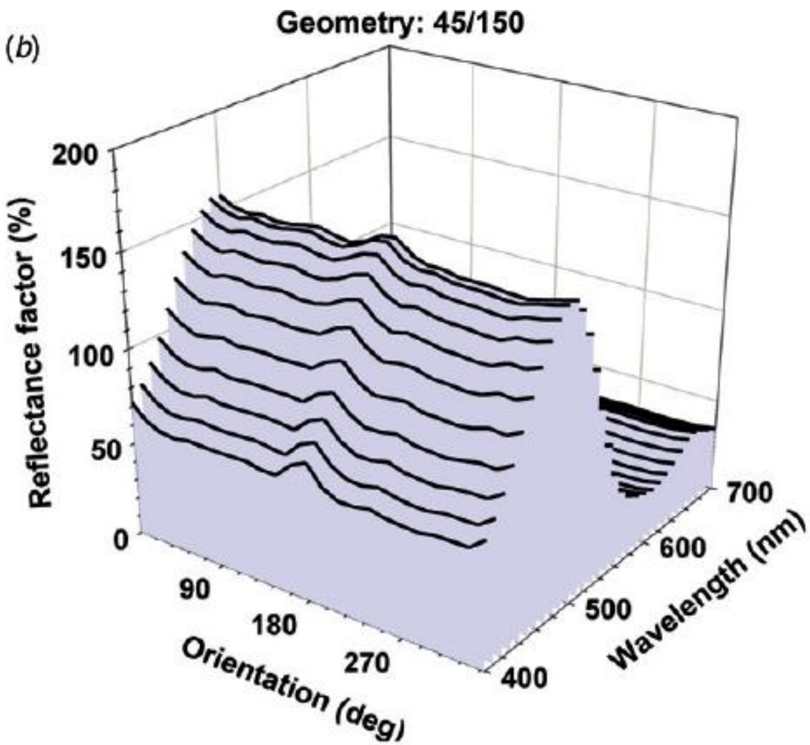
Optical anisotropy in flake pigments

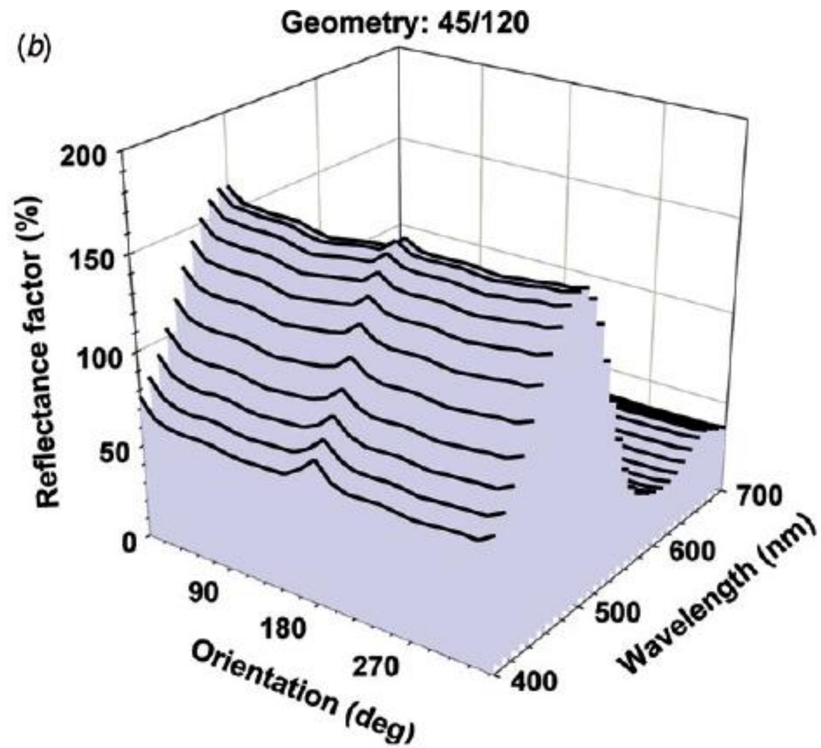
- **Results (VII): metallic blue sample**



Optical anisotropy in flake pigments

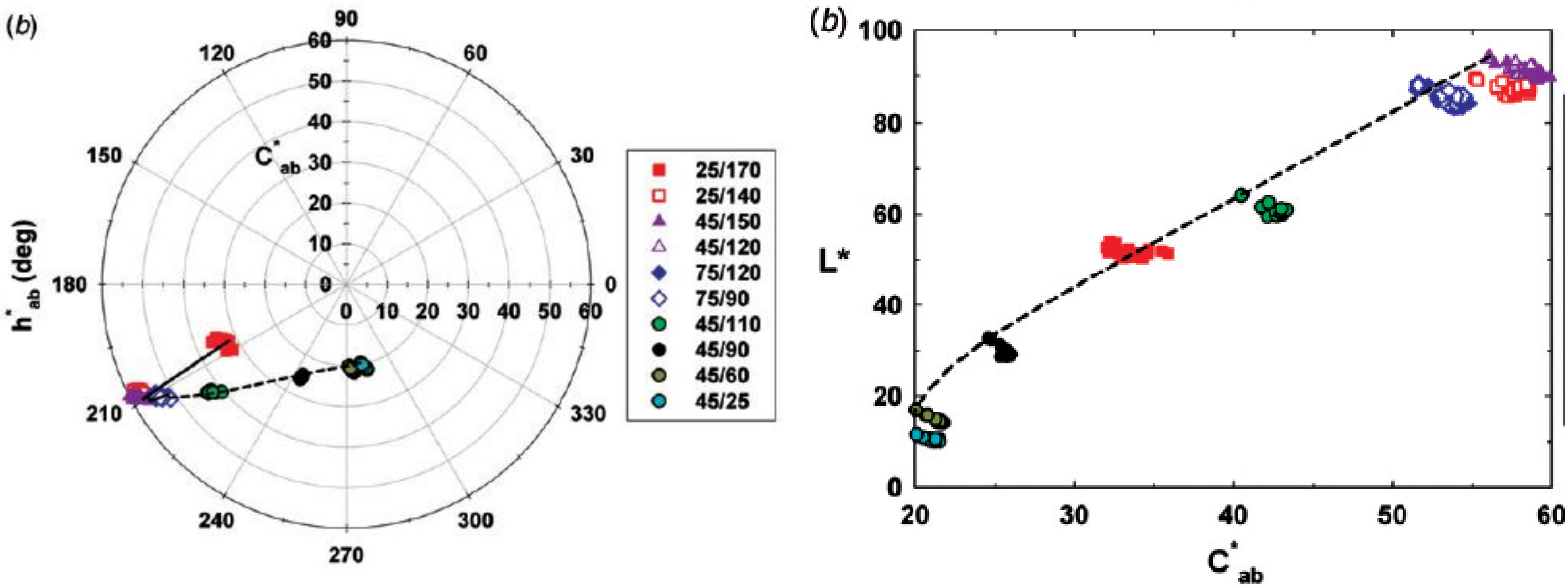
- **Results (VIII): 3D spectral data**
- **Geometries 45/120 vs. 45/150 deg**





Optical anisotropy in flake pigments

- Results (IX): all orientations & geometries



Optical anisotropy in flake pigments

- **Are these color differences perceptible?**

Table 2. Differences of colorimetric coordinates between angles associated to the aspecular geometry (45/150, trans) of pearlescent and metallic samples.

	Pearlescent sample				Metallic sample			
Angle pair	ΔL^*	ΔC^*_{ab}	ΔH^*_{ab}	ΔE_{ab}	ΔL^*	ΔC^*_{ab}	ΔH^*_{ab}	ΔE_{ab}
0°–180°	+12.37	+5.15	0.00	13.40	−0.48	−0.73	−0.04	0.87
15°–195°	+11.98	+5.18	+0.47	13.06	+0.23	−0.76	−0.05	0.80
30°–210°	+11.58	+4.80	0.00	12.54	+0.66	−0.96	−0.10	1.17
45°–225°	+9.92	+4.01	0.00	10.70	+0.88	−0.60	−0.40	1.14
60°–240°	+6.73	+2.66	+0.36	7.25	+0.98	−0.58	+0.03	1.14
75°–255°	+3.42	+1.35	+0.36	3.69	+1.18	−0.54	−0.06	1.30
90°–270°	+0.44	+0.15	0.00	0.46	+1.66	−0.37	−0.06	1.70
105°–285°	−2.67	−1.20	−0.36	2.95	+1.97	+0.14	−0.17	1.98
120°–300°	−5.69	−2.37	+0.36	6.17	+1.27	+0.39	−0.07	1.33
135°–315°	−9.08	−3.73	0.00	9.82	+0.47	+0.32	−0.37	0.68
150°–330°	−11.31	−4.52	0.00	12.18	+0.29	+0.84	+0.43	0.99
165°–345°	−12.61	−5.28	0.00	13.67	+1.05	+0.90	−0.10	1.38

Optical anisotropy in flake pigments

- **Are these color differences perceptible?**

Table 4. Colour differences ΔE_{ab} for the pearlescent sample viewing in two complementary azimuth angles for 10 measurement geometries.

Angle pair	25°/170°	25°/140°	45°/150°	45°/120°	75°/120°	75°/90°	45°/110°	45°/90°	45°/60°	45°/25°
0°–180°	4.71	12.31	13.40	14.25	15.50	17.17	13.50	5.26	0.94	0.41
15°–195°	3.84	12.18	13.06	14.18	15.31	16.85	13.05	5.69	0.86	0.39
30°–210°	4.57	11.89	12.54	13.26	14.45	15.61	12.29	5.01	0.83	0.43
45°–225°	4.32	10.30	10.70	11.27	12.38	13.23	10.71	4.25	0.88	0.41
60°–240°	3.08	7.15	7.25	7.89	8.84	9.32	7.40	3.30	0.57	0.21
75°–255°	1.70	3.98	3.69	4.12	4.90	4.83	3.69	2.17	0.30	0.19
90°–270°	1.09	1.06	0.46	0.60	1.08	1.17	0.53	0.46	0.11	0.22
105°–285°	1.45	2.68	2.95	3.28	3.30	3.81	3.97	1.83	0.47	0.33
120°–300°	1.12	5.74	6.17	6.66	6.87	7.65	7.27	3.00	0.73	0.24
135°–315°	2.85	9.02	9.82	10.37	11.16	11.86	10.67	4.68	0.87	0.30
150°–330°	3.78	11.24	12.18	12.93	14.09	15.13	12.99	5.30	0.96	0.41
165°–345°	4.64	12.59	13.67	14.70	15.65	17.43	14.21	5.60	1.06	0.50

Optical anisotropy in flake pigments

- Discussion (I): spectral data
- Relative reflectance factor
  - Reflectance scale higher to 100 for some geometries and orientations
- Shift of peaks towards longer wavelengths from “trans” to “cis”
- There is not spectral reversibility between angle pairs like 0-180, 15-195, …, 90-270 deg, etc
- Spectral profiles are constant with orientation, for all geometries

Optical anisotropy in flake pigments

- **Discussion (II): colorimetric data**

- **Interference line:**
  - Trans (+15º) and Cis (-15º) from specular direction
  - Sudden change of hue in these directions

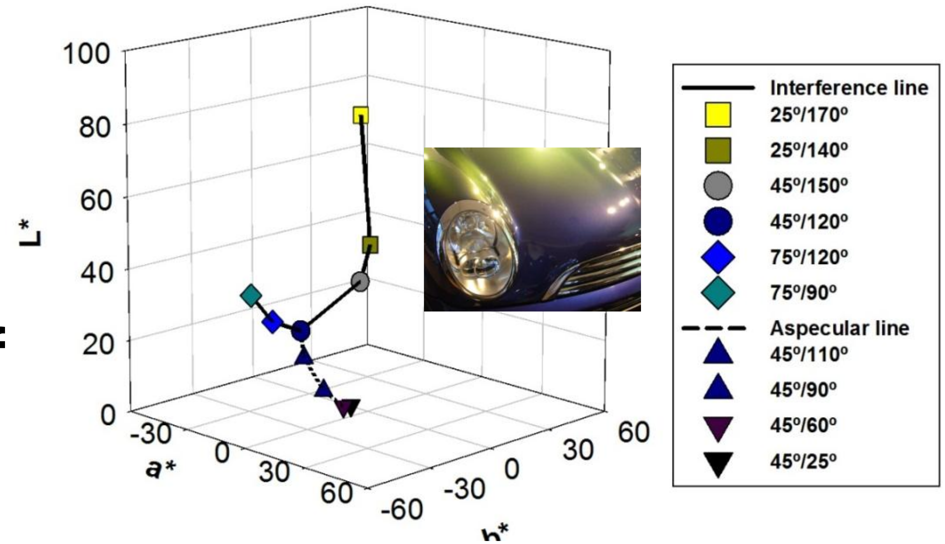
- **Aspecular line**
  - Same incidence angle, different reception angles
  - Increasing change of lightness and chroma, with slight variation of hue angle

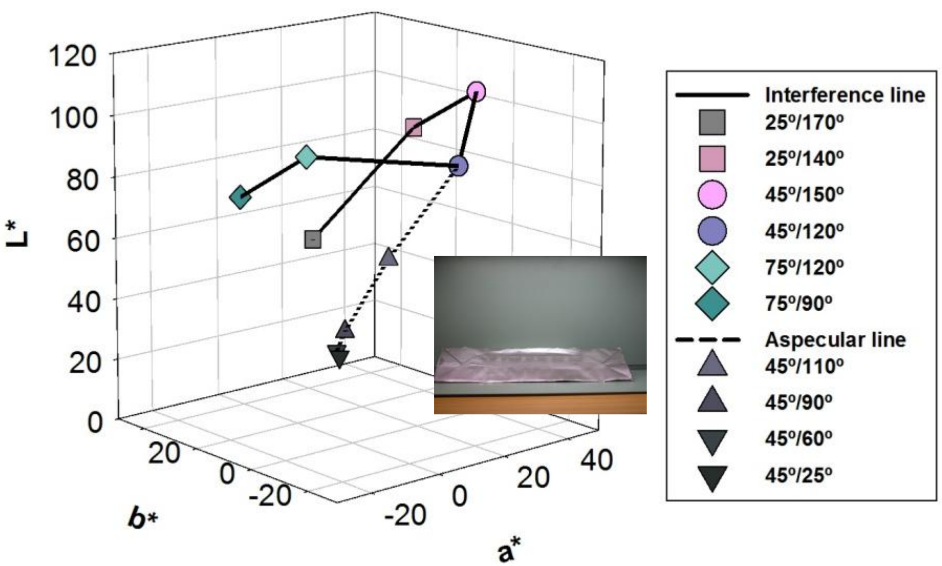
Optical anisotropy in flake pigments

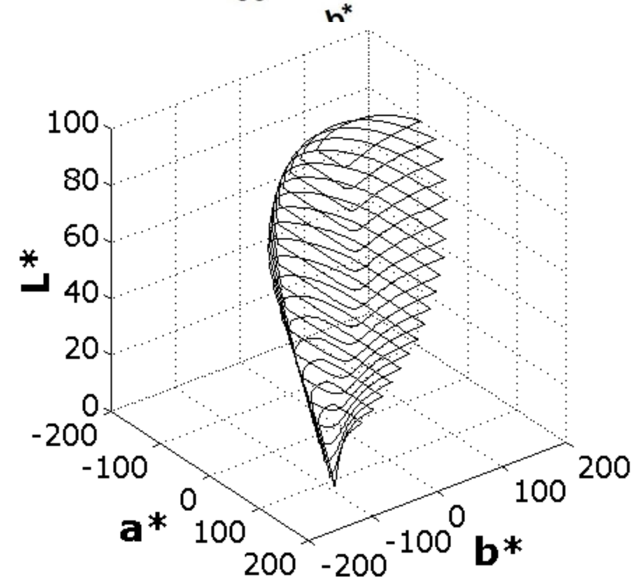
- Discussion (III): colorimetric data
- All orientations & geometries:
  - Constant hue angle
- Failure of chromatic reversibility between orientation pairs
  - “Trans” geometries:
    - 0 – 165 deg: from lighter – stronger to darker – weaker
    - 180 – 345 deg: vice versa
  - “Cis” geometries:
    - From darker – weaker to lighter – stronger, and vice versa

Color gamuts outside theor. color solid

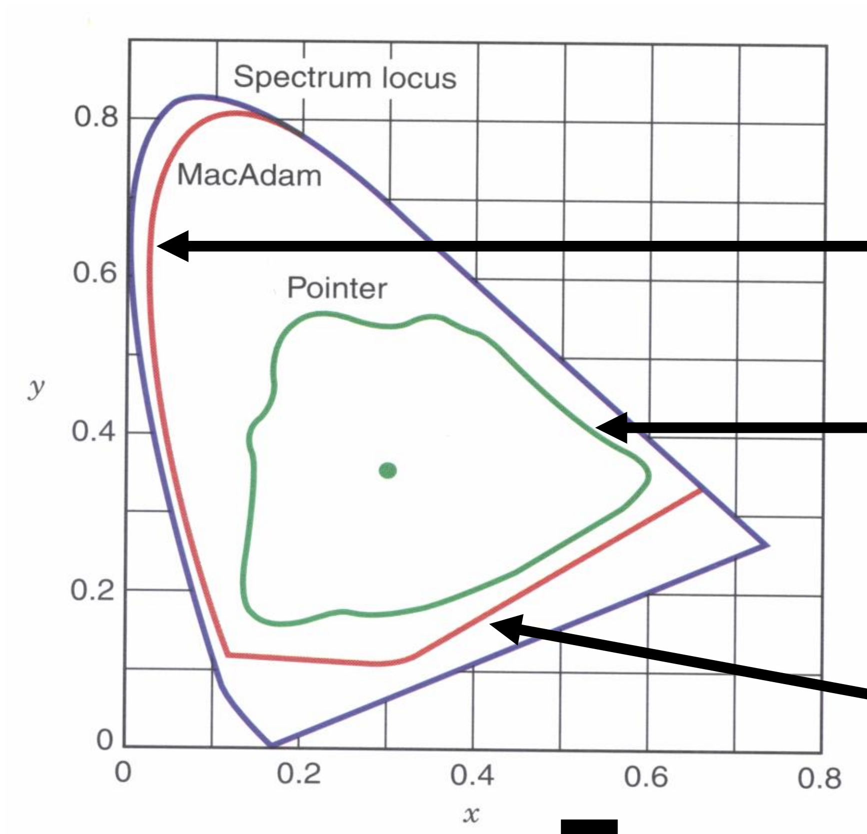
- **Purpose:**
- **Are these special color samples into or outside of MacAdam/Pointer limits?**

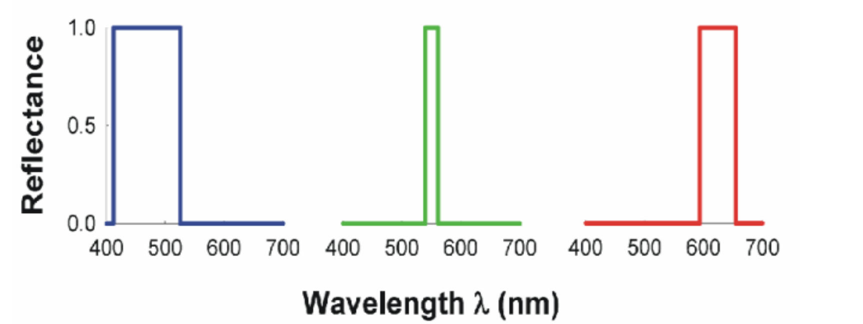






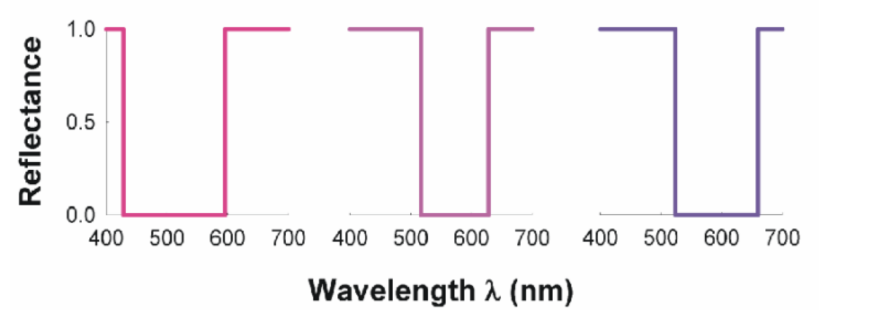
Color gamuts outside theor. color solid





real colors,

smooth spectral data



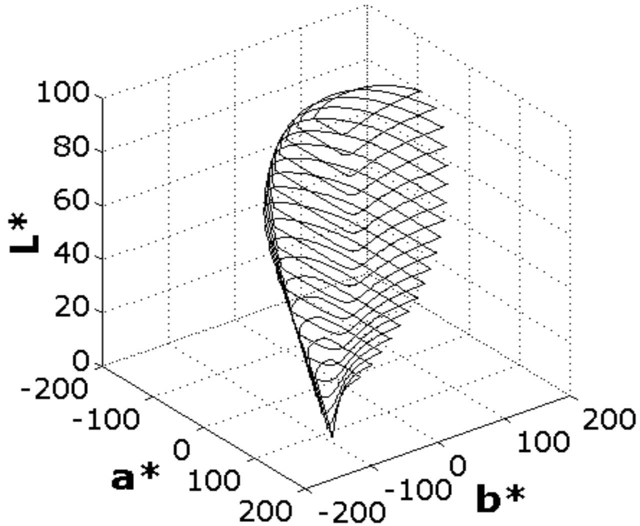
and the gonio-apparent samples?

Color gamuts outside theor. color solid

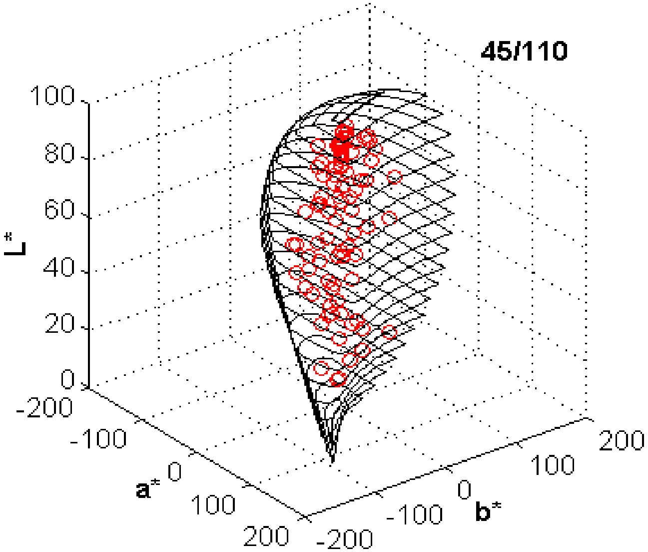
- Database→ 91 samples from commercial catalogues:
  – Merck, BASF Coatings, etc

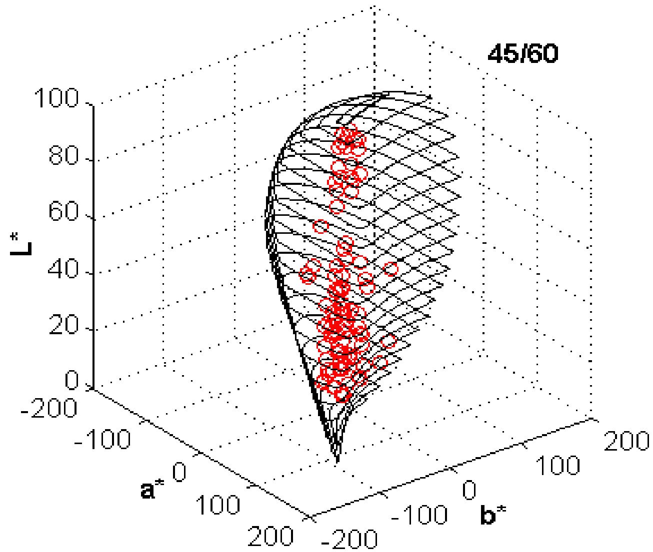
- Instrument → multi-gonio-spectrophotometer Datacolor FX10

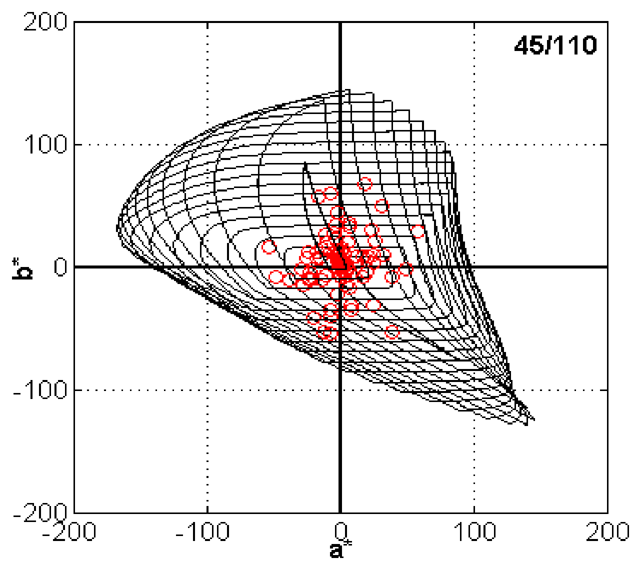
- Color solid
  – CIE-L*a*b*, D65, CIE-1964

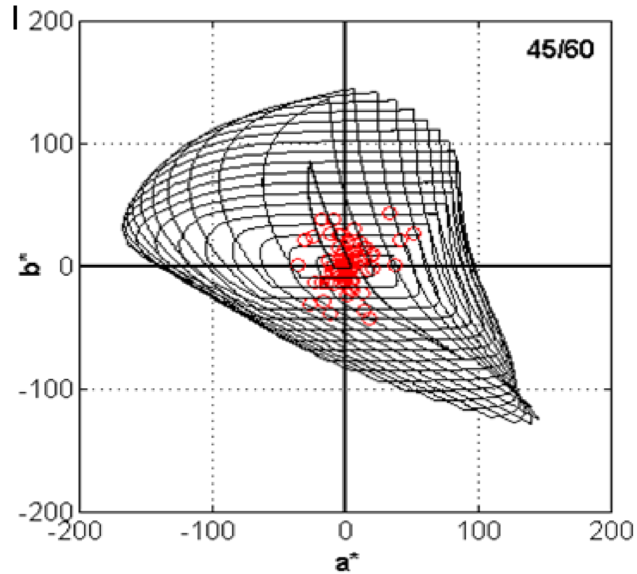


Results in aspecular lines

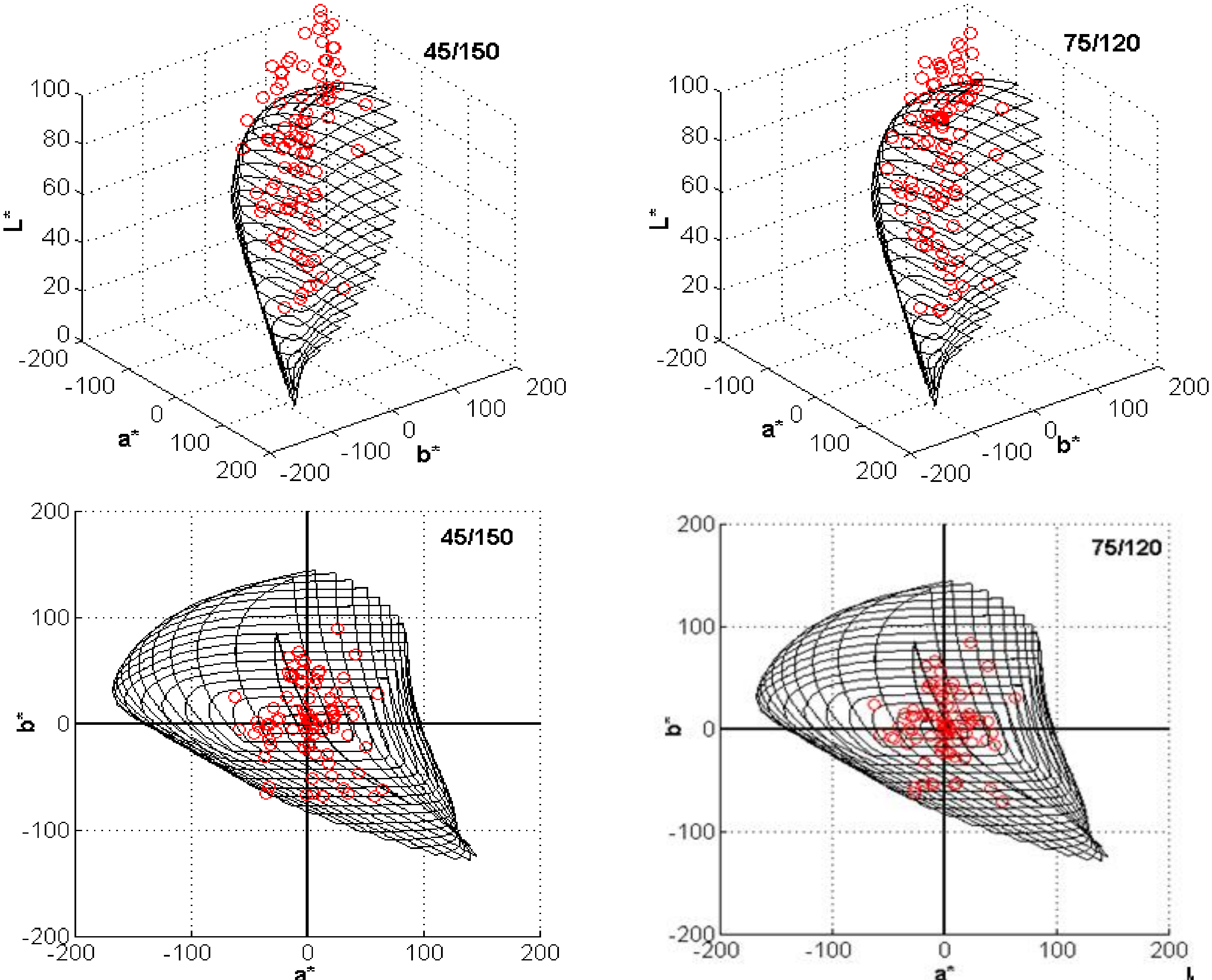






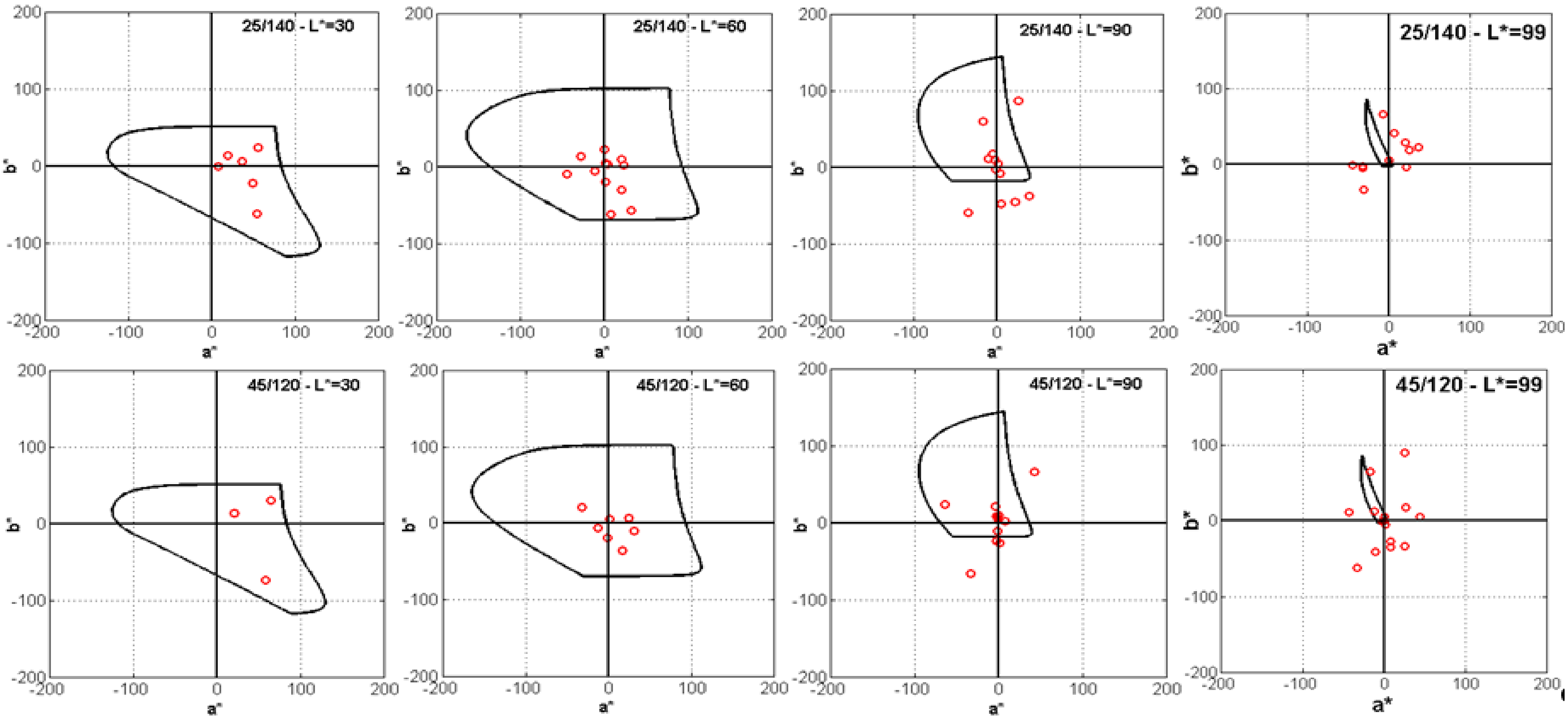


Results in interference lines



Results in constant L* planes

Top: 25/140 geometry, L* planes: 30, 60, 90 and 99

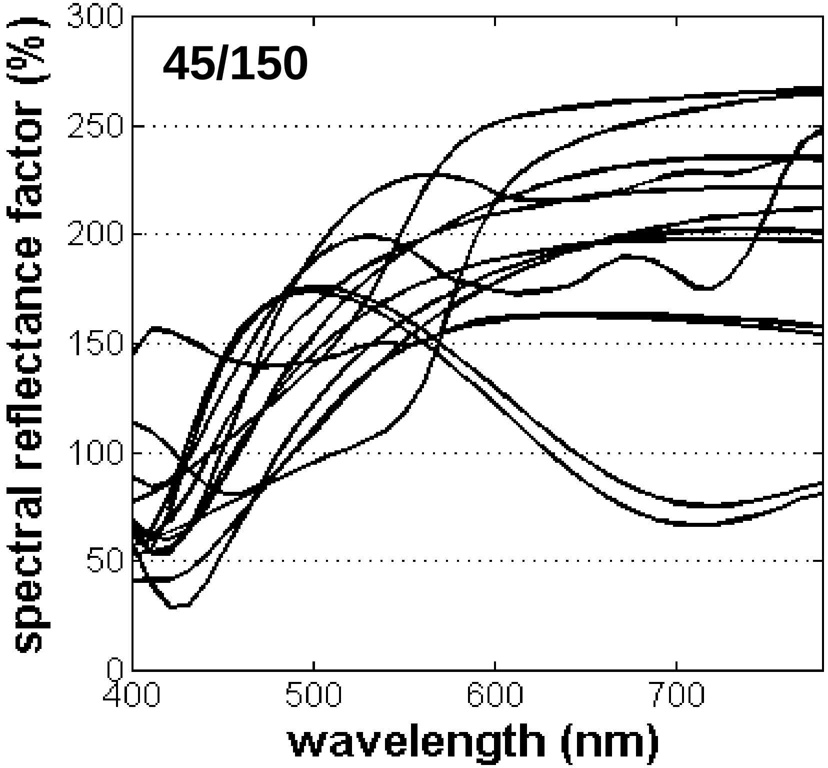


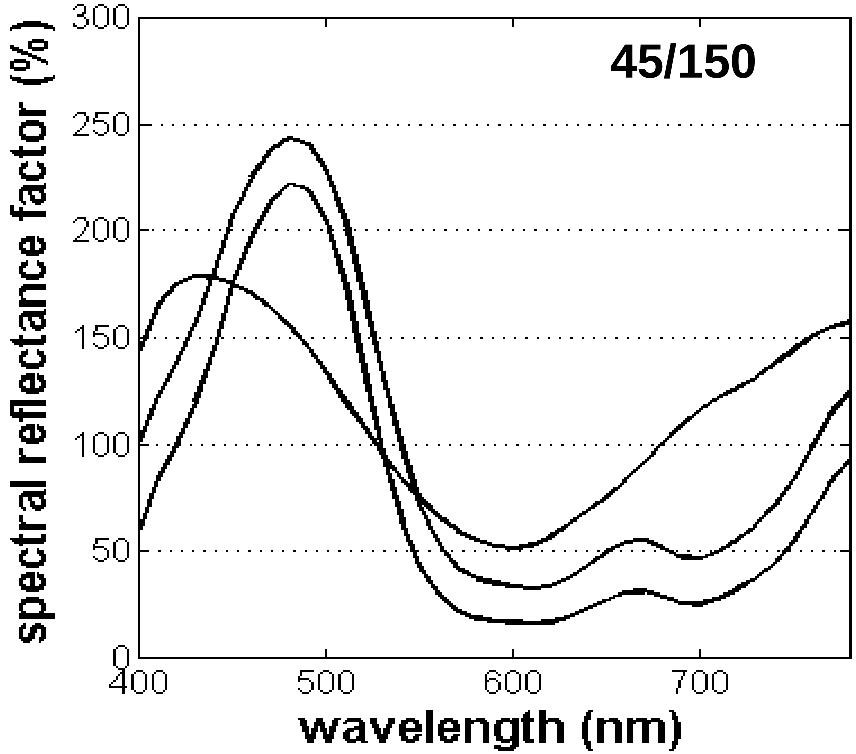
Bottom: 45/120 geometry, L* planes: 30, 60, 90 and 99

Spectral reflectances of gonio-samples

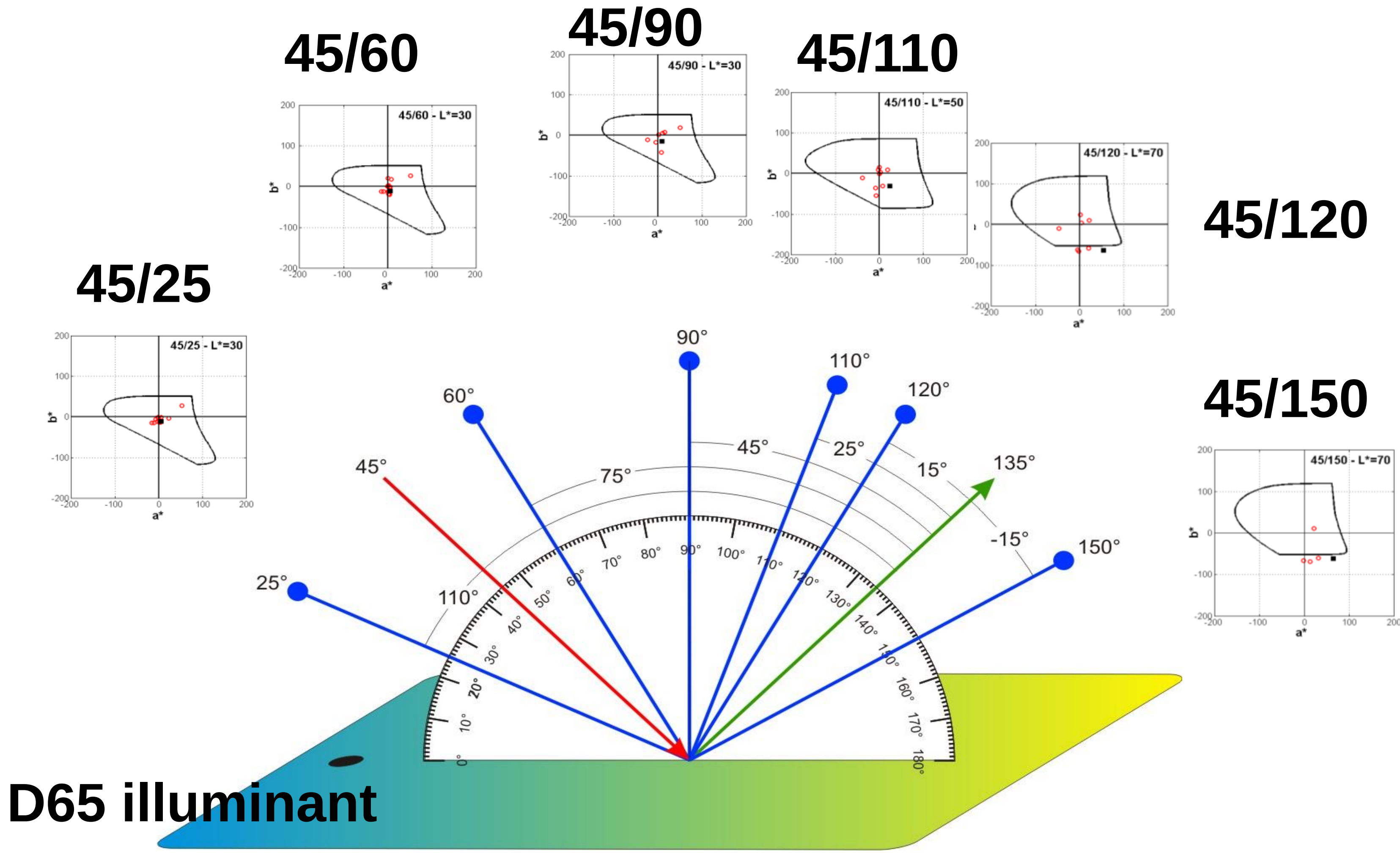
$\rho(\lambda) > 150\ \% \rightarrow L^* > 100$

$\rho(\lambda) > 150\ \%$ but $L^* < 100 \rightarrow C^*_{ab} > C^*_{ab,\ MacAdam}$

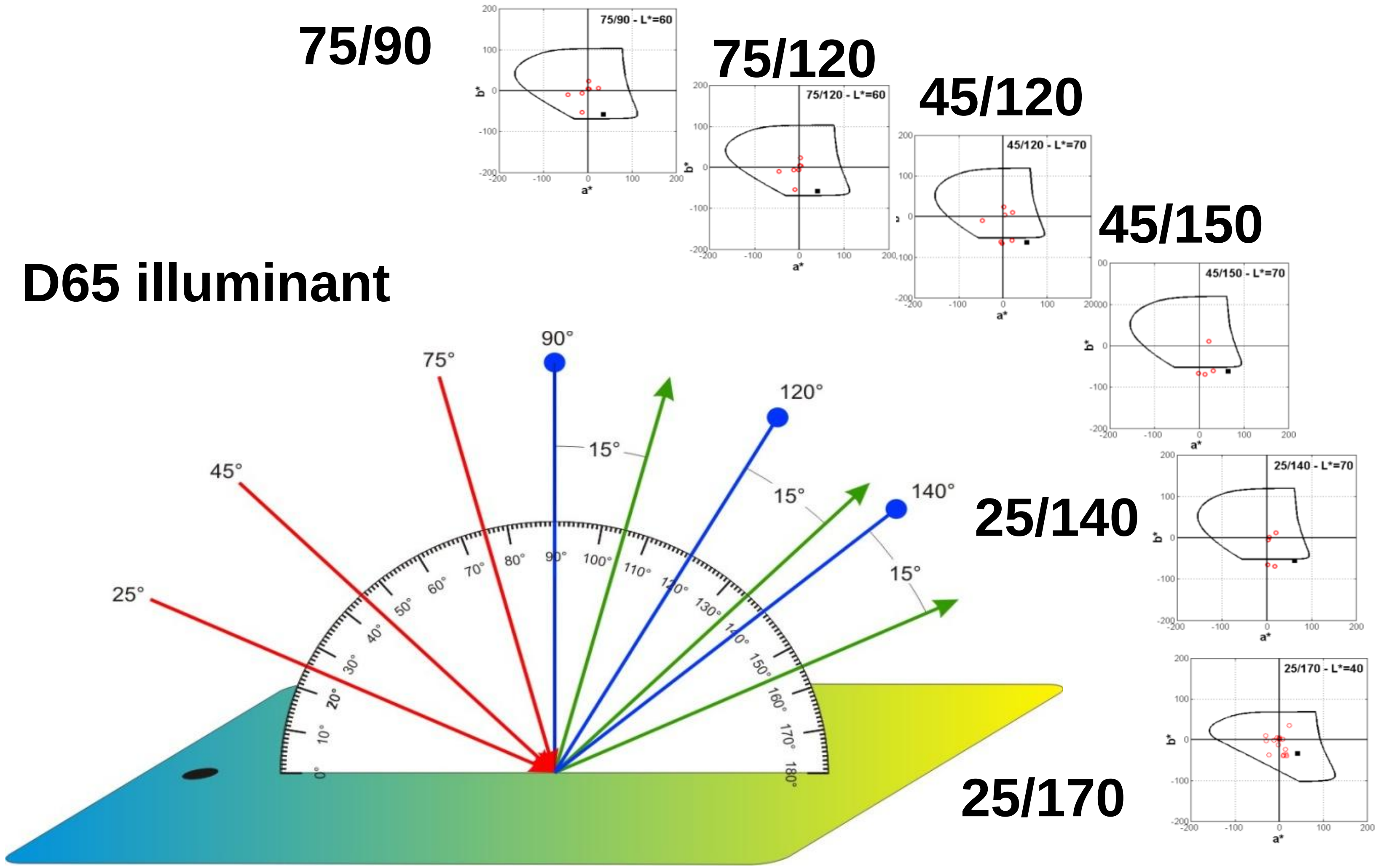




“Road” across aspecular geometries

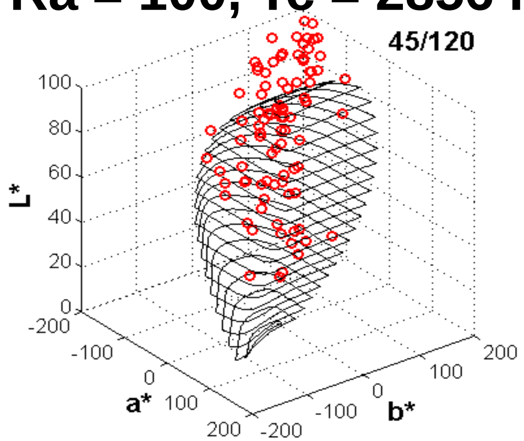


"Road" across interference geometries

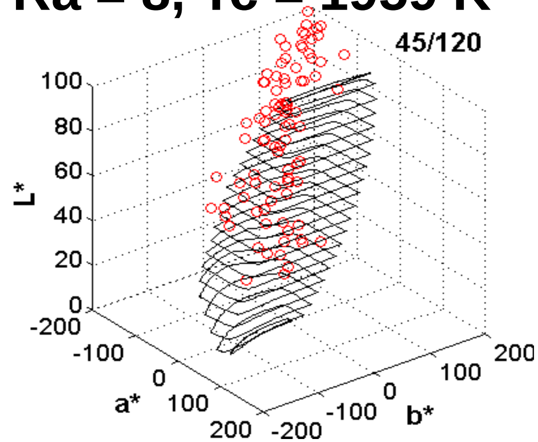


Varying light source

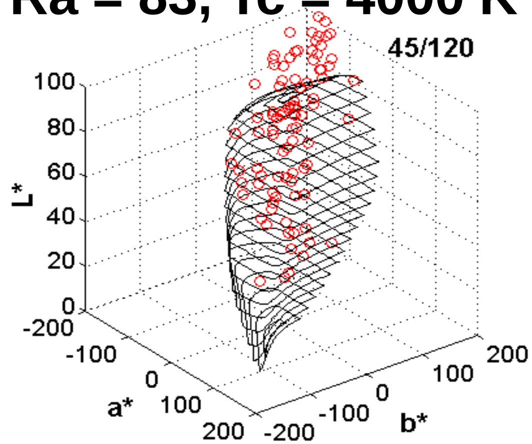
Illuminant A
Ra = 100, Tc = 2856 K



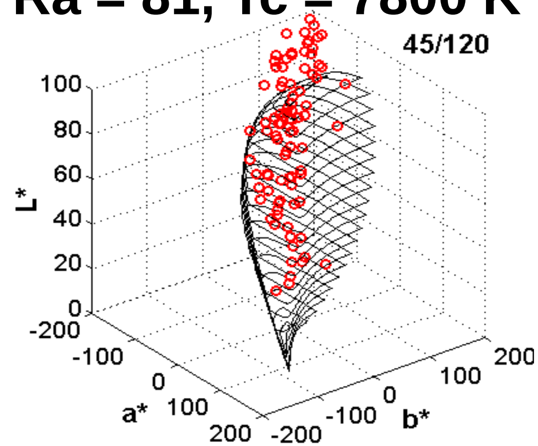
Lamp HP1
Ra = 8, Tc = 1959 K



Illuminant F11
Ra = 83, Tc = 4000 K

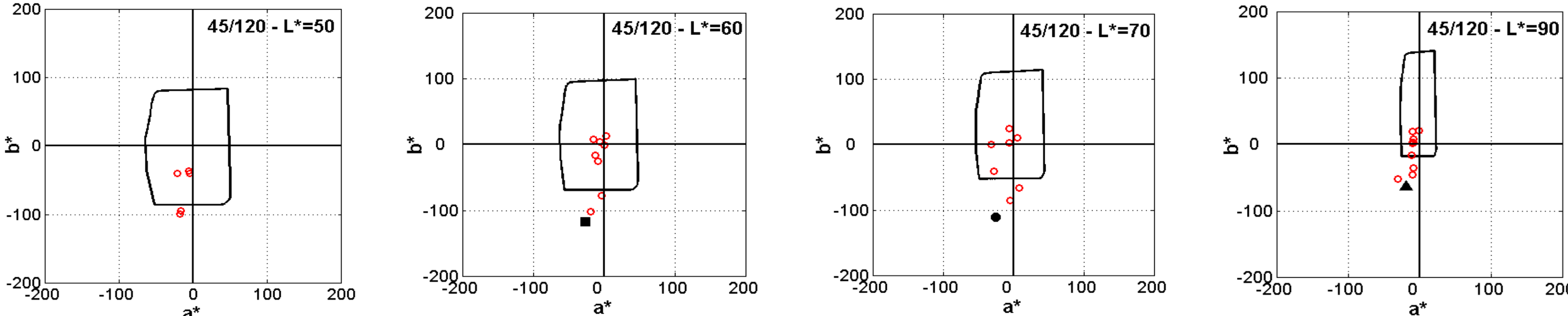


Lamp wLED
Ra = 81, Tc = 7800 K

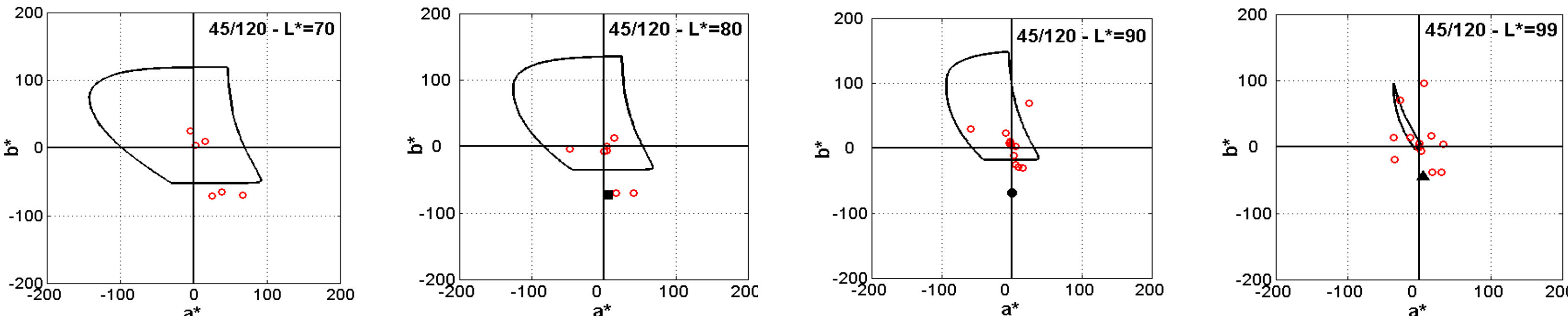


Varying light source

- **Some gonio-samples (different symbols for 3 special samples) in chromaticity diagrams with some lightness planes at 45/120 geometry**



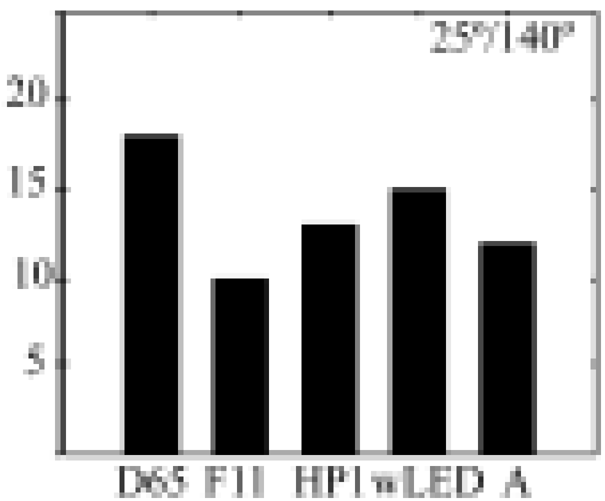
HP1 lamp, L* planes: 50, 60, 70 and 90

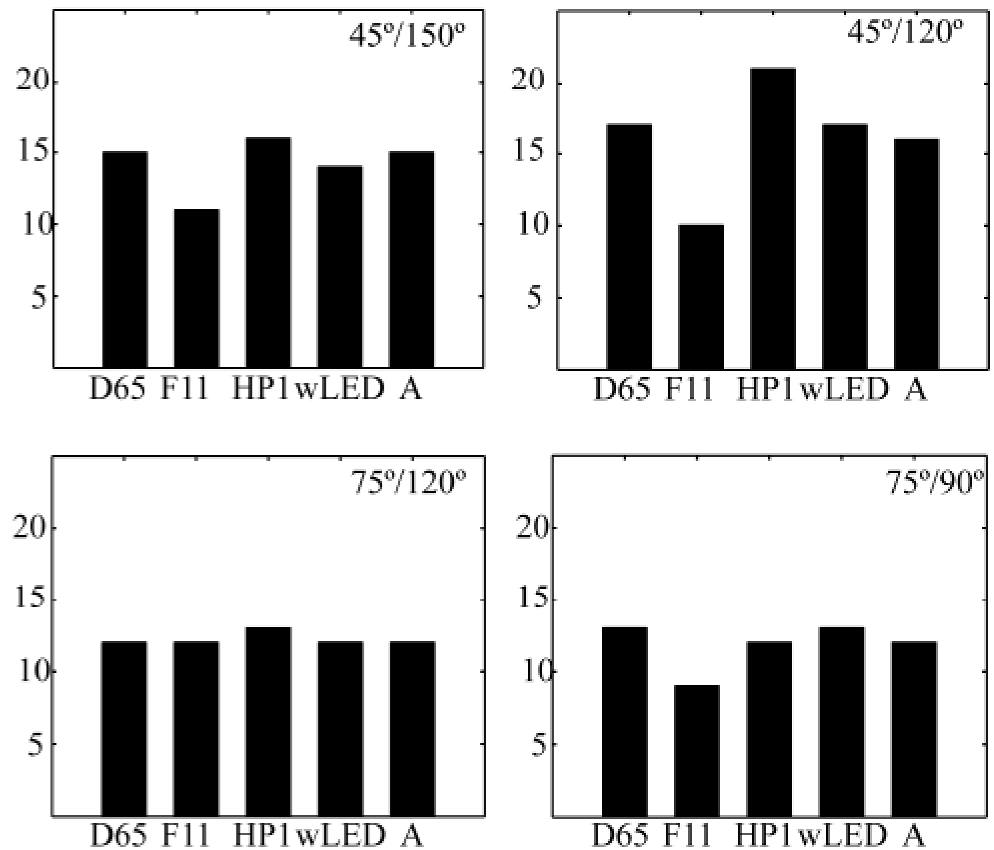


wLED lamp, L* planes: 70, 80, 90 and 99

Varying light source

- **Number of samples outside of MacAdam limits for different light sources and different geometries with $C^*_{ab}{}^* > C^*_{ab,\,MacAdam}$**





Color gamuts outside theor. color solid

- **Conclusions:**
- **There are chromatic perceptions outside MacAdam limits, even simultaneously for some illuminants and real light sources**
  - **Interference lines is very important at metrological level**
  - **There are gonio-samples with $C^* > C^*_{MacAdam}$, with $L^* < 100$**
  - **Valid for any out-of-plane geometry?**
  - **For any special-effect pigment?**
- **Therefore, the concept of classical optimal color, from Rösch-MacAdam theory, should be revised**

Color gamuts outside theor. color solid

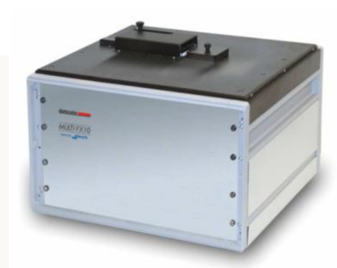
- **Future perspectives:**
- **Great opportunities for Design, Arts, Architecture and Computer Graphics**
  - **Will can future digital color technologies offer these new chromatic perceptions?**
  - **At spectral or colorimetric level?**

- **Which spectral dynamic ranges provide chromatic encodings outside of MacAdam limits for many illuminants and light sources?**

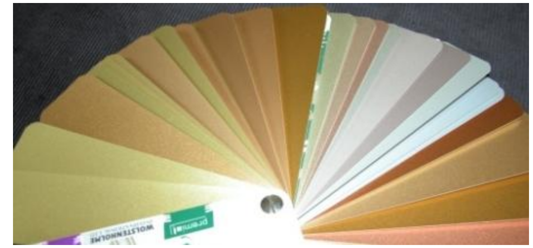
- **Which 3D measurement geometries would be interesting for these topics?**

Reproducibility between multi-gonios

- **Purpose:**
  - To compare the reproducibility of some multi-gonio-spectrophotometers following the ASTM E2214-08 rules for the common geometries
  - Available instruments: comparisons by pairs
    - X-Rite MA68II and X-Rite MA98
    - Datacolor FX10
    - BYK-mac



Reproducibility between multi-gonios



- **Materials and Methods:**
- **Database of 88 gonio-apparent samples**
- **Measure conditions: 20 times without replacement for the four instruments**
- **Calculation of the relative reflectance factors and colorimetric coordinates (illuminant D65, CIE-1964 standard observer)**
- **Calculation of the partial and total colour differences in CIELAB color space**
- **Statistical studies: Hotelling's test and the inter-comparison-test (ASTM E2214-08)**

Reproducibility between multi-gonios

- **Statistical inter-comparison test:**

Critical Value $t_{\Delta E} = \sqrt{\dfrac{\chi_3^2}{n \cdot g_E}}$, $n = 88$

χ^2 → chi-square value for 3 degree of freedom

n → total of measurements

g_E → parameter calculated by the following equation:

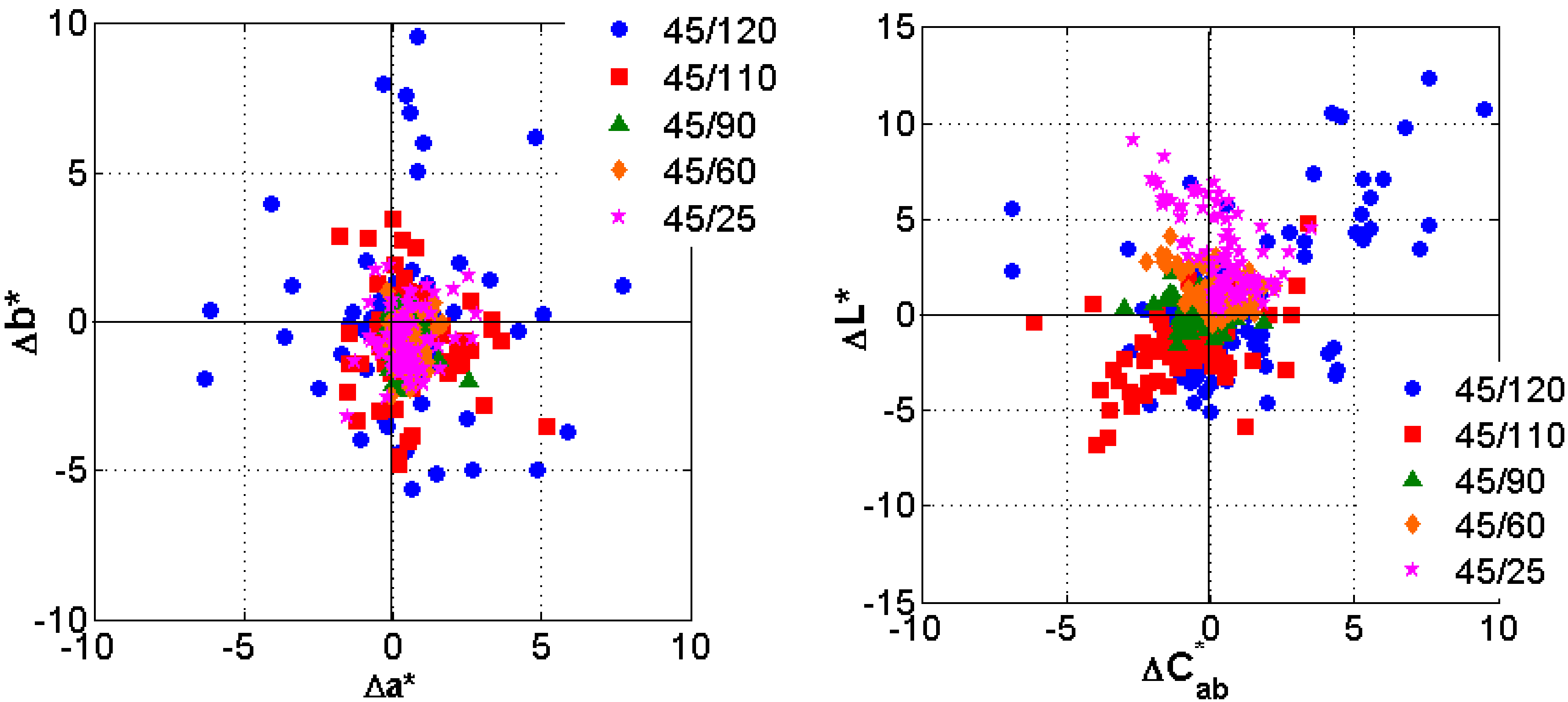
$$g_E = g_{11}\alpha^2 + g_{22}\beta^2 + g_{33}\gamma^2 + 2g_{12}\alpha\beta + 2g_{23}\beta\gamma + 2g_{13}\alpha\gamma$$

$$\alpha = \frac{mean(\Delta L^*)}{mean(\Delta E_{ab})}, \quad \beta = \frac{mean(\Delta a^*)}{mean(\Delta E_{ab})}, \quad \gamma = \frac{mean(\Delta b^*)}{mean(\Delta E_{ab})}$$

if Average(ΔE_{ab}) > $t_{\Delta E}$ ⇨ statistically significant

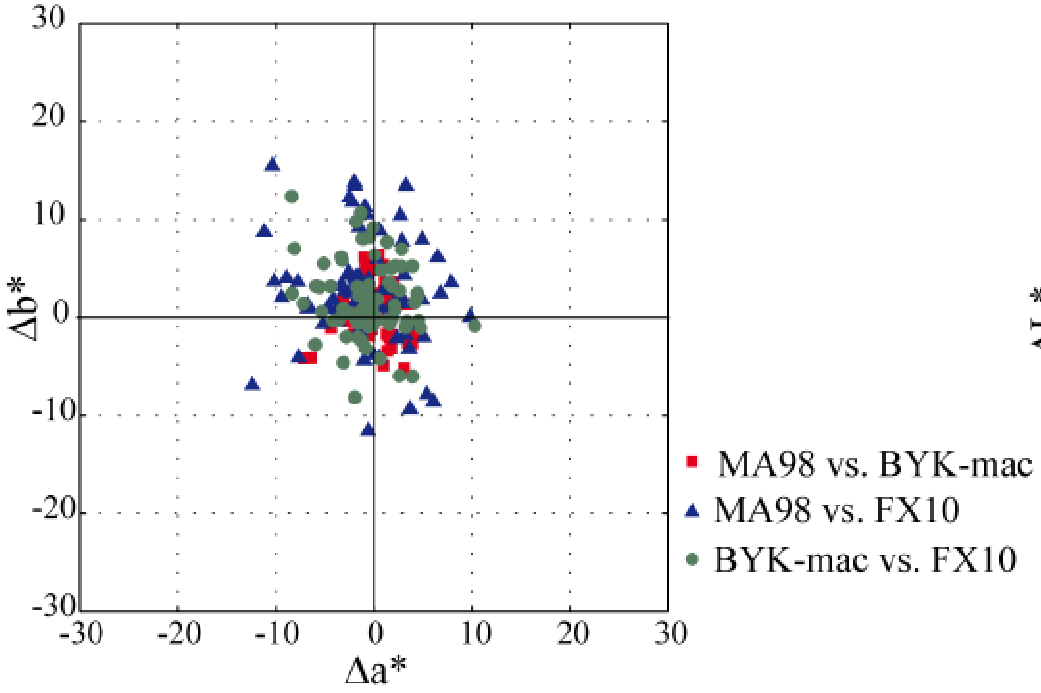
Reproducibility between multi-gonios

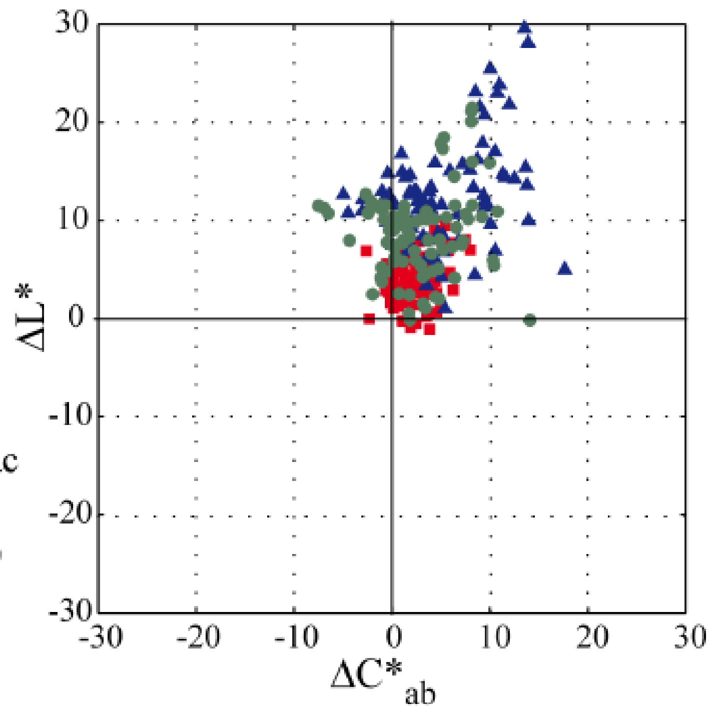
- **Results: MA98 vs. FX10**
  - **Are these color deviations from identical gonio-apparent samples systematic or random (non-statistically significant)?**



Reproducibility between multi-gonios

- **Results: MA98 vs. mac vs. FX10 for 45as-15**
  - **Are these color deviations from identical gonio-apparent samples systematic or random (non-statistically significant)?**





Reproducibility between multi-gonios

- **Results: MA98 vs. mac vs. FX10 for 45as-15**
  - **Are these color deviations systematic or random (non-statistically significant)?**
  - **Test: if $\Delta E_{ab} < t_{\Delta E} \Rightarrow$ statistically not significant differences**

45°x:-60° (as -15°)	*MA98 vs. BYK- mac*			*MA98 vs. FX10*			*BYK- mac vs. FX10*		
	ΔL*	Δa*	Δb*	ΔL*	Δa*	Δb*	ΔL*	Δa*	Δb*
Average	3.87	1.37	2.01	12.55	3.08	4.26	8.75	2.31	2.92
|Max|	9.47	7.16	6.45	29.58	12.44	15.50	21.53	10.29	12.35
|Min|	1.09	4.03	5.15	1.02	9.82	11.56	0.18	8.40	8.15
P		0.000			0.000			0.000	
$t_{\Delta E}$		0.806			1.622			0.037	
$\overline{\Delta E^*_{ab}}$		4.988			14.278			10.169	

Reproducibility between multi-gonios

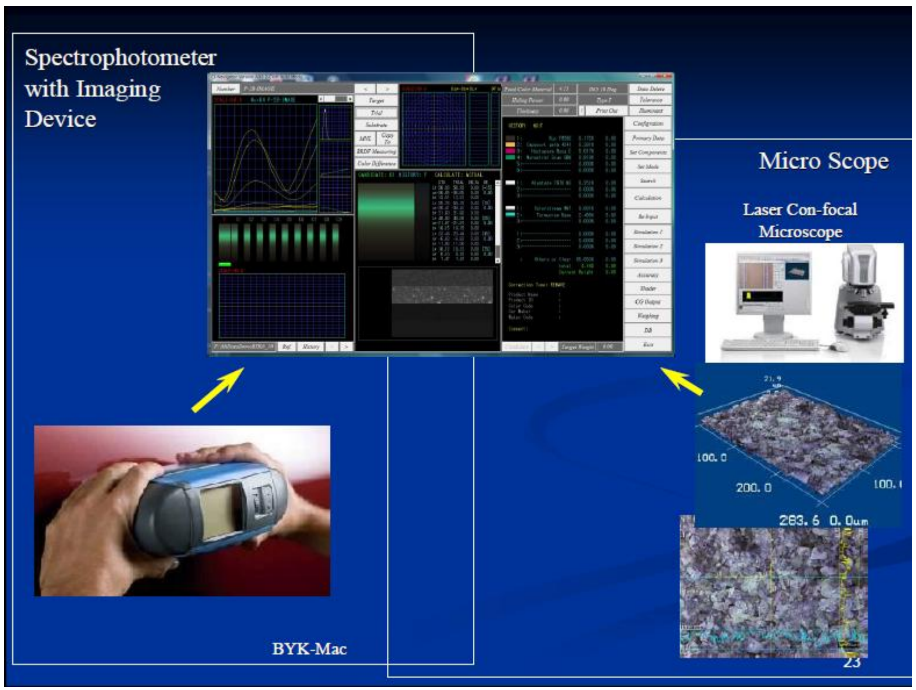
- **Conclusions: MA98 vs. mac as the best pair**
- **Most of the measurement geometries are statistically significant → angle tolerances, photometric scales, white standards, etc.**
- **Both statistical tests are not valid to discriminate and quantify the detected bias errors**
- **Intrinsic difficulty to find efficient methods for comparing the reproducibility in multi-gonio-spectrophotometers**

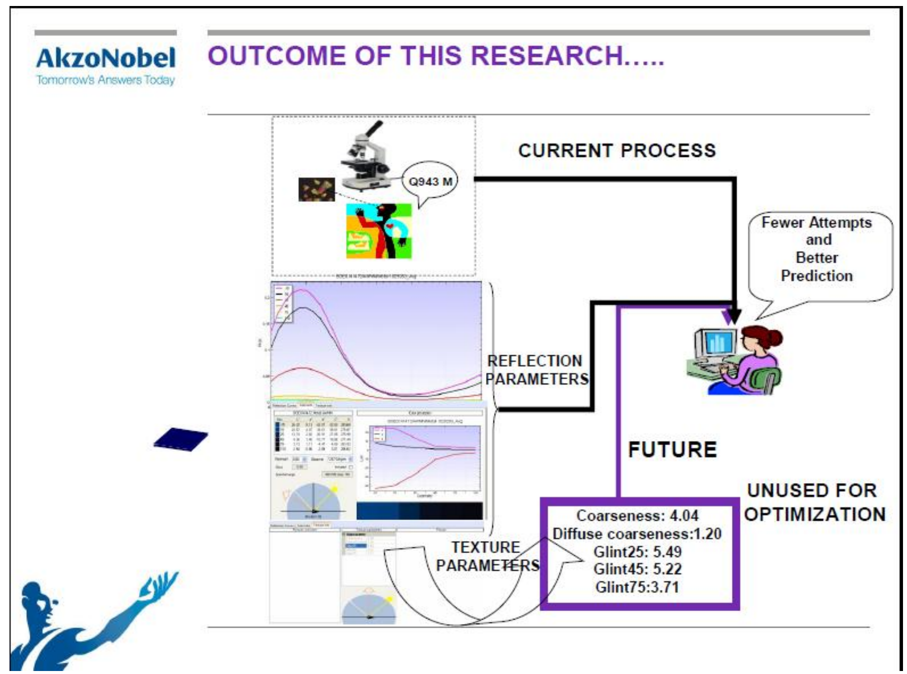
Outline

- **What is? How is it measured and perceived?**
  - **Current instrumentation and standards**
- **How these visual effects are caused by?**
- **New findings from the GVC-UA**
- **Future challenges:**
  - **Modeling and prediction of visual appearance**
  - **New materials and process technologies**
  - **Visual appearance matching control management**

Modeling and prediction of visual appearance

- Color formulation of special-effect pigments
  - Calculation of color recipes (concentrations) for obtaining the final desired color (and texture)





Modeling and prediction of visual appearance

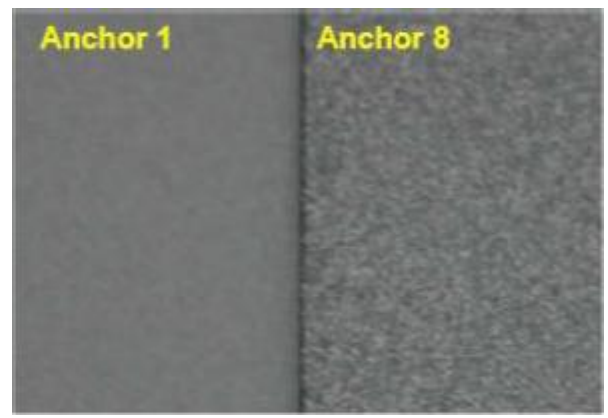
- **Coarseness (graininess) model from AZKNCoatings:**

AkzoNobel
Tomorrow's Answers Today

DIFFUSE COARSENESS

$$
\begin{aligned}
DC_{LinReg1} = {} & \alpha_0 + \alpha_1 ConcC + \alpha_2 OM_{110}\Sigma K_{Metallic} + \alpha_3 OM_{110}\Sigma K_{pearl} + \alpha_4 OM_{110}\Sigma S_{Metallic} \\
& + \alpha_5 OM_{110}\Sigma S_{pearl} + \alpha_6 OM_{25}\Sigma\left(1/R\right) + \alpha_7 OM_{25}\Sigma(R) + \alpha_8 OM_{25}\Sigma\left(R^2\right) + \alpha_9 OM_{25}\Sigma S_{Metallic} \\
& + \alpha_{10} OM_{25}\Sigma\left(\sqrt{R}\right) + \alpha_{11} OM_{45} L^* + \alpha_{12} OM_{45}\Sigma K_{Metallic} + \alpha_{13} OM_{45}\Sigma(R) + \alpha_{14} OM_{45}\Sigma S_{Metallic} \\
& + \alpha_{15} OM_{45}\Sigma S_{pearl} + \alpha_{16} OM_{45}\Sigma\left(\sqrt{R}\right) + \alpha_{17} OM_{25}\Sigma K / \Sigma S
\end{aligned}
$$

OM: Optical Model
ConC: Summed concentration of the non-effect toners in the formula
OMgeoKMetallic: Summed ci-Ki values at a given geometry for metallic toners.
OMgeoSMetallic: Summed ci-Si values at a given geometry for metallic toners.
OMgeoKPearl: Summed ci-Ki values at a given geometry for Pearl toners.
OMgeoSPearl: Summed ci-Si values at a given geometry for Pearl toners.
OMgeoΣR: predicted reflection values summed over all wavelengths at geometry.
OMgeoL*: predicted CIE lightness at a geometry



Modeling and prediction of visual appearance

- **Glint (sparkle) model from AZKNCoatings:**

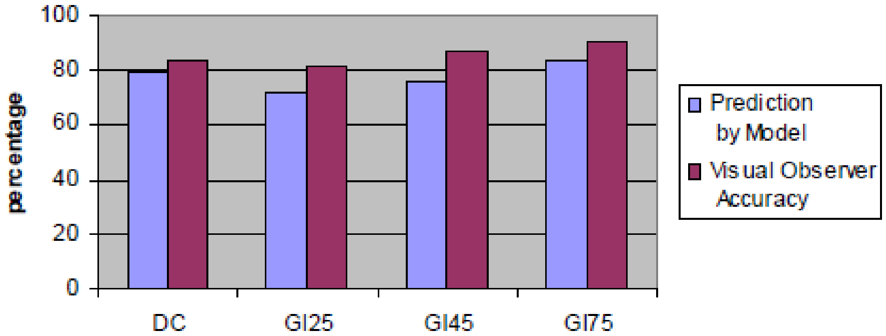
AkzoNobel

Tomorrow's Answers Today

GLINT IMPRESSION MODEL

$$
\begin{aligned}
GI_{LinReg1} = {} & \alpha_0 + \alpha_1 ConcC + \alpha_2 ConcPearl + \alpha_3 OM_{110} CieC + \alpha_4 OM_{110} CieL + \alpha_5 OM_{110} \Sigma K_{Metallic} \\
& + \alpha_6 OM_{110} \Sigma K_{pearl} + \alpha_7 OM_{110} \Sigma R + \alpha_8 OM_{110} \Sigma R^2 + \alpha_9 OM_{110} \Sigma S_{Metallic} + \alpha_{10} OM_{110} \Sigma S_{pearl} + \alpha_{11} OM_{110} \Sigma \sqrt{R} + \\
& \alpha_{12} OM_{110} \Sigma S_{solid} + \alpha_{13} OM_{110} X + \alpha_{14} OM_{110} Y + \alpha_{15} OM_{25} Ciea + \alpha_{16} OM_{25} Cieb + \alpha_{17} OM_{25} Cieh \\
& + \alpha_{18} OM_{25} \Sigma K_{Metallic} + \alpha_{19} OM_{25} \Sigma K_{pearl} + \alpha_{20} OM_{25} \Sigma K_{solid} + \alpha_{21} OM_{25} \Sigma S_{metallic} + \alpha_{22} OM_{25} \Sigma S_{Solid} / \Sigma K_{Solid} \\
& + \alpha_{23} OM_{25} X + \alpha_{24} OM_{25} Y + \alpha_{25} OM_{45} Ciea + \alpha_{26} OM_{45} CieC + \alpha_{27} OM_{45} CieL + \alpha_{28} OM_{45} \Sigma K_{Metallic} \\
& + \alpha_{29} OM_{45} \Sigma K_{Pearl} + \alpha_{30} OM_{45} \Sigma R + \alpha_{31} OM_{45} \Sigma R^2 + \alpha_{32} OM_{45} \Sigma S_{Metallic} + \alpha_{33} OM_{45} \Sigma S_{Pearl} \\
& + \alpha_{34} OM_{45} \Sigma\left(\sqrt{R}\right) + \alpha_{35} OM_{45} \Sigma S_{Solid} + \alpha_{36} OM_{45} Z + \alpha_{37} OM_{25} \Sigma K / \Sigma S + \alpha_{38} OM_{45} \Sigma K / \Sigma S
\end{aligned}
$$

X, Y Z are the tristimulus values corresponding to each angle and L, a , b , C and h are the color parameters



Modeling and prediction of visual appearance

- **Total color + texture difference formulae:**
- **From Zhejiang & Leeds: Chinese Opt. Lett. 2010**
  - **Diffuse vs. directional illumination:**

$$\Delta T = \sqrt{\sum_{i=1}^{6} c_i (\Delta E^*{}_i)^2 + c_7 (\Delta \mathrm{Coarseness})^2}$$

$$\Delta T = \sqrt{c_1 (c_2 \Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}) + c_3 \Delta \mathrm{Glint}^2}$$

Modeling and prediction of visual appearance

- **Total color + texture difference formulae:**
- **From AzkoNobel Car Refinishes: Col Res Appl 2011**
  - **Visual assessment of color and texture vs. total difference formula:**

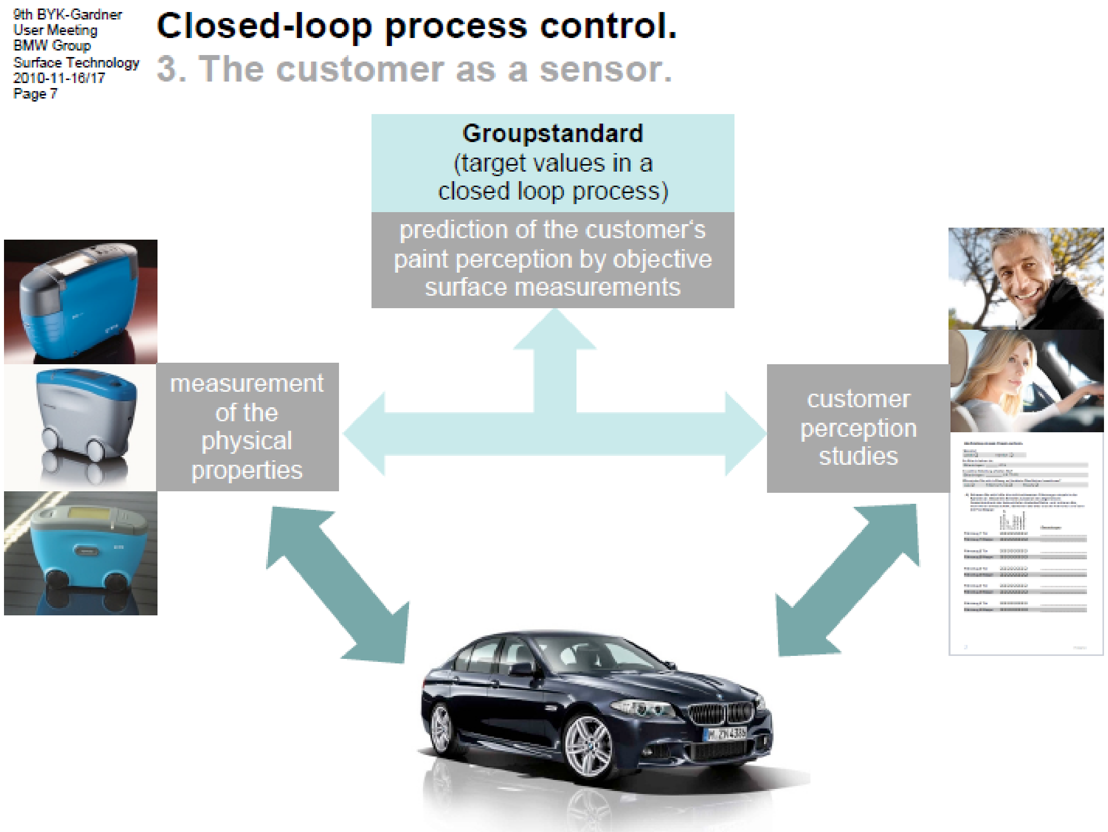
$$\mathrm{CDG} = a + \sum_{i=1}^{6} b_i \cdot dE_i + \sum_{j=1}^{3} c_j \cdot \Delta GI_j + d \cdot \Delta DC$$

$$\mathrm{TADiF} = \sum_{i=1}^{6} b'_i \cdot dE_i + c'_1 \cdot \Delta GI_1 + c'_3 \cdot \Delta GI_3 + d' \cdot \Delta DC$$

$$\text{with } \sum_{i=1}^{6} b'_i + c'_1 + c'_3 + d' = 1 \quad (5)$$

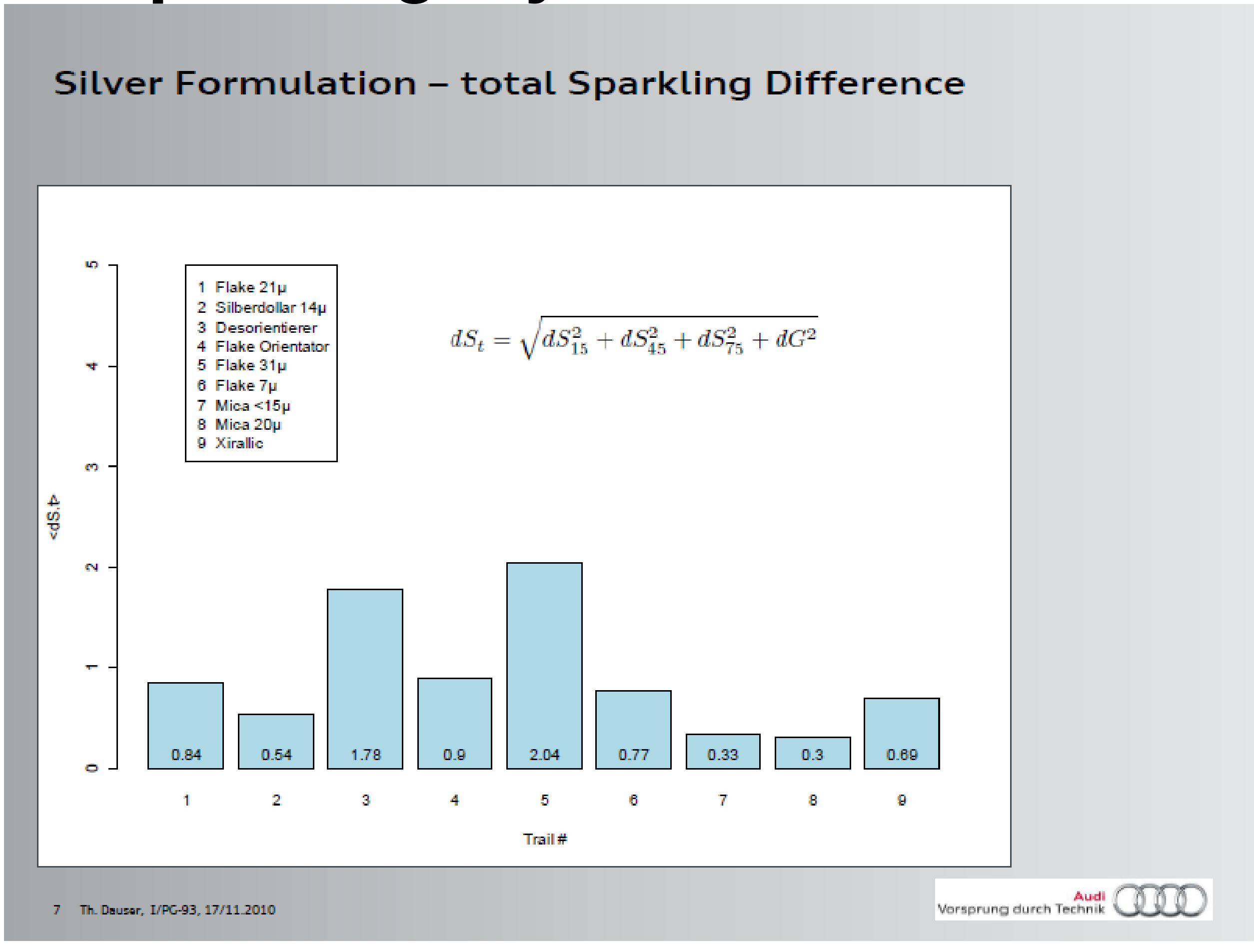
Visual scales of color + texture

- **Customer as a sensor, by BMW:**



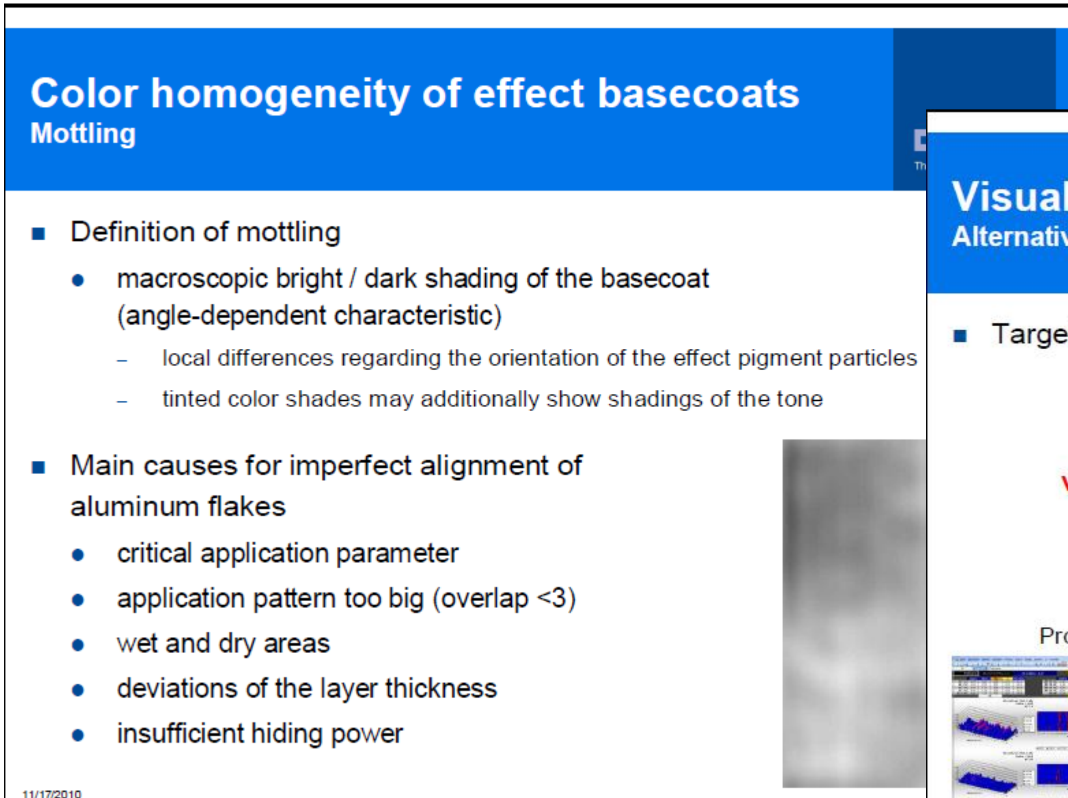
Visual scales of color + texture

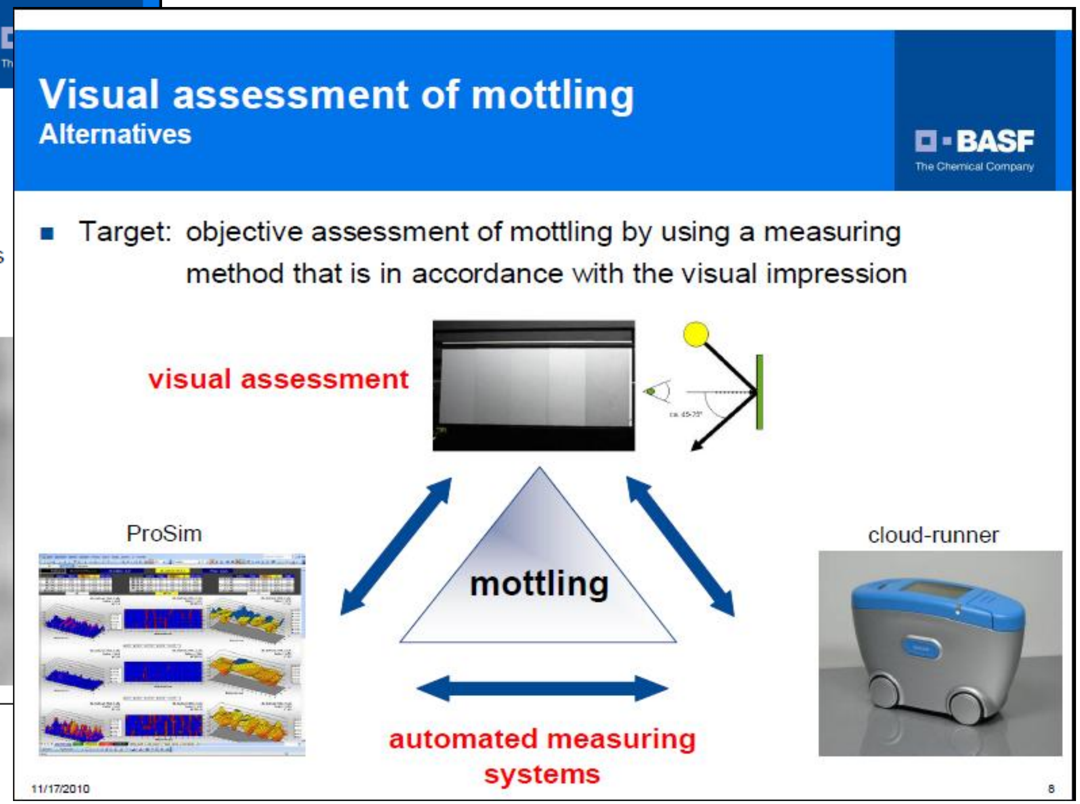
- **Total difference of sparkling, by Audi:**
  - **Why euclidean?**



Visual scales of color + texture

- **Evaluation of mottling (cloudiness), by BASF Coat.**





New materials and process technologies

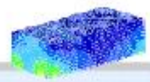
- Design and fabrication of special colors outside MacAdam color solid ??
  - Prediction model for these special colors?
  - Visual anisotropies ??
- New special-effect pigments from Nature ??
- Processing control of special-effect pigments
  - Better management of reproducibility in fabrication

Visual appearance matching control management

Goal of today and tomorrow

→ Uniformity and Top Quality

Automotive Maker
Part Supplier
Paint Maker
Raw Material Maker
BYK-Gardner



Challenge:

- New material and process technologies
- Efficient color & appearance control management

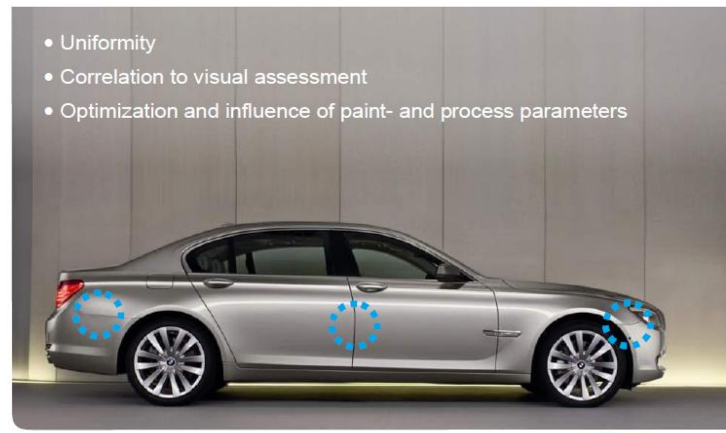
The whole is more than the sum of the individual parts.

BYK Additives & Instruments

Page 12, BYK-Gardner, Introduction

9th BYK-Gardner User Meeting

Harmony: Uniform Color & Appearance



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BYK Additives & Instruments

Conclusions

- Goniochromism is a very active field of color science & technology with large impact in automotive industry and affine sectors
- Spectral and color characterization of special-effect pigments is complicated, as well as its visual appearance (color + texture)
- Many challenges for next decades, which needs the effort and coordination of companies and research centers (universities, etc.)

References

- All contributions of W.R. Cramer, worldwide color consultant in special-effect pigments (1999 -).
- Contributions shown in the past 9th BYK-Gardner User's meeting (Bad Tölz, November 2010).
- G. Pfaff: *Special Effect Pigments*. Norwich: William Andrew Publishers, 2008.
- E. B. Faulkner & R.J. Schwartz: *High Performance Pigments*, 2nd ed. Wienheim: Wiley-VCH, 2009.
- H.J. Streitberger, K.F. Dössel: *Automotive Paints and Coatings*, 2nd ed. Wienheim: Wiley-VCH, 2008.

Additional references

- G.A. Klein: *Industrial Color Physics.* New York: Springer, 2010.
- GVC-UA contributions (2009 -): http://web.ua.es/en/gvc .
- Z. Huang, H. Xu, M.R. Luo, G. Cui, H. Feng: "Assessing total differences for effective samples having variations in color, coarseness, and glint". *Chinese Opt Lett*, 8, 7, 717-720 (2010).
- N. Dekker, E.J.J. Kirchner, R. Supèr, G.J. van den Kieboom, R. Gottenbos: "Total Appearance for Metallic and Pearlescent Materials: Contributions from Color and Texture". *Color Res Appl*, 36, 1, 4-14 (2011).
- ASTM standards cited in this presentation.

¡¡ Thank you for your attention !!

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